DETERMINATION OF CREEP, FATIGUE AND AGEING CHARACTERISTICS OF NON-METALLIC STRENGTH MEMBERS IN OPTICAL COMMUNICATION CABLES

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ABSTRACT

Innovative tensile, creep, fatigue, environmental weathering and ageing test methods have been developed to compare the ultimate and relative performances of four commercial brands of non-metallic continuous multi fibre strength member yarns, and one jointed non-metallic multi fibre strength member yarn. The main materials under investigation were two commercial brands of the para-aramid polymer yarn polyparaphenylene terepthalate, also investigated were ultra high molecular weight polyethylene (UHMWPE) and E glass.

Assessment of the materials has been made in the light of current theories on the mechanical and chemical performance. Comparisons are made between the properties of jointed aramid yarn and virgin yarn material. A comparison of the tensile and creep performances of aramid in laboratory yarn tests and with fully manufactured communication cables containing the same aramid material is made.

The results of the investigations indicate a very similar performance of different aramid brands in all areas. The aramid materials proved to be the best all round non-metallic peripheral strength members. UHMWPE offered good ageing and abrasion resistance but exhibited a high creep rate. E glass suffered greatly from the effects of mechanical abrasion but possessed the lowest creep rate of all the materials tested.

The tensile performance of a finished cable type was analysed in terms of composite axial moduli resulting from aramid and central GRP rod contributions. The creep rate and performance of a finished cable type was found to be the same as that accepted for the constituent strength member yarn indicating an absence of undesirable mechanical changes such as core gripping. Jointed aramid is shown to offer the same tensile and creep performance benefits as virgin aramid but in fatigue tests the joints pulled apart indicating unsuitability of the type of joint used for aerial applications. Aramid was found to be the most suitable material for use as a non-metallic strength member in aerial, internal, duct and direct buried applications.

CONTENTS

GLOSSARY OF TERMS

A	Cross sectional area [m^2]
ADSS	All dielectric self supporting
AWT	All weather testing
c_s	creep rate [%/s]
decitex	Mass in grams of 10,000 m of yarn
DERV	Diesel engined road vehicle
DOF	Degrees of freedom
E	Young's Modulus [Pa]
e	Material extension [mm]
E_s	Specific modulus [N/tex]
EWF	Environmental weathering frame
ϵ	Strain [%]
F	Applied force [N]
GRP	Glass reinforced polymer
H	Creep activation energy [J/mol]
H0	Hypothesis
H1	Null hypothesis
Hz	Unit of frequency hertz (cycles per second)
IDS	Inductive Displacement Sensor
K	Creep scaling constant (Eqn. 2.6)
LASE	Load at specified elongation [N]
l	Specimen original length or gauge length [mm]
LD	Linear density unit decitex [dtex]
M	Yarn bobbin weight [kg]
m	Mass [kg]
m_c	Constant (Eqn. 2.7)
m_w	Weibull shape parameter
MNP	Solvent for aramid base polymers (chemical name not known)
MSBR	Maximum Speed of Bobbin Rotation [rpm]
N	Number of test samples

n	Creep equation material constant
$\mathbf{n_t}$	N^{th} sample from a population of test samples
OWF	Outdoor weathering frame
Pf	Probability of Failure [%]
Ps	Probability of Survival [%]
PIB	Polyisobutylene
PID	Proportional integral and differential amplifier
PPD	Paraphenylene diamine base monomer
PPTA	Polyparaphenylene Terepthalate
ρ	Material density [g/cm^3]
R	Universal gas constant [8.314 J mol^{-1} K^{-1}]
r	Photodegradation constant (Eqn. 2.5)
$\mathbf{R_g}$	Radius of bobbin gyration [m]
r.h.	Relative humidity [%]
σ	Mechanical stress [MPa]
σ_b	Breaking strength after a specified time [MPa]
σ_f	Weibull Scale Parameter [MPa]
σ_o	Initial breaking strength [MPa]
σ_n	Weibull normalising parameter [MPa]
σ_u	Weibull measured failure stress [MPa]
SSW	Saturated salt water
T	Absolute temperature [K]
t	Time [s or logsec]
TDC	Terephthaloyl dichloride base monomer
tex	Weight in grams of 1000 m of yarn
Tg	Glass transition temperature [K or °C]
TM	Twist multiplier
TW	Twist in turns per meter [n/m]
UHMWPE	Ultra High Molecular Weight Polyethylene
UTS	Ultimate tensile strength [MPa]
u.v.	Ultra violet

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1.0 INTRODUCTION

Most optical communication cables require strength member materials to facilitate installation into ducts or for mechanical support in aerial and other applications. All dielectric aerial and duct type cables utilise rigid highly orientated polymeric, E-glass or composite materials with engineered tensile properties. Materials and processes such as jointing and the application of surface coatings can be used on non-metallic strength members but the consequences of such treatments have not been fully understood.

The object of this thesis has been to improve the understanding of non-metallic strength member material performance with time. The task has been considered in terms of tensile mechanical properties, mechanical creep, mechanical fatigue and ageing characteristics. To meet the project requirements it was essential that novel mechanical testing methods were developed and applied to yarn materials.

Non-metallic strength member materials such as para-aramid yarns are generally applied peripherally by a stranding process over cable cores containing a central glass reinforced polymer rod and a number of tubes containing optical fibres. The core and strength member combination is sheathed prior to winding onto a drum. Duct type cable is drawn from the drum by the strength member or sheath and installed into a duct where the strength member is no longer under tension but the cable may be required to be reinstalled into another duct at a later date. A duct may be flooded or dry and consequently cables may be subject to the ageing effects of water and contaminated water. Aerial cable is pulled from the drum and suspended by the strength members from poles or other raised structures. The cable is subject to mechanical tensile loading and vibration. The work carried out as part of this investigation is important in the prediction of conditions and design factors that influence product lifetimes which are now being specified by manufacturers within the communication cable industry.

The approach adopted was to conduct a literature review and then develop novel test methods in accordance with relevant standards where possible. Test methods were developed with flexibility in mind so that new materials and processes can be included at any time. Creep and fatigue testing was carried out on material yarns including jointed material yarns and finished cables, comparisons will be drawn between the different sets of results.

Four commercial brands of yarn have been studied, with special emphasis being given to the aramid materials which form the core of this investigation. Aramid and E-glass were chosen as they are used widely within the communication cable industry as non-metallic peripheral strength members. The UHMWPE Dyneema was selected as a potential new non-metallic strength member for use in communication cables. The brand names appear in the reviewed literature. The brands of yarn material consist of two brands of lyotropic liquid crystal para-aramid polymer yarn (Polyparaphenylene Terepthalate PPTA), known as aramid [4]. The two brands of aramid were Akzo Twaron Type 1055 (1610 dtex) and DuPont Kevlar 49 Type 989 (1580 dtex).

One brand of Ultra High Molecular Weight Polyethylene (UHMWPE) yarn was chosen, DSM Dyneema SK65 (1760 dtex). A brand of E-glass yarn (borosilicate glass) was selected for creep testing. The brand was Owens Corning OFY 680 (6294 dtex).

2.0 LITERATURE REVIEW

The following review introduces some of the underlying concepts in mechanical testing of rigid high molecular orientation polymer yarns. The main mechanical properties considered are those relating to mechanical creep, mechanical fatigue, tensile performance and material ageing. Mechanical creep is defined as [1] : The time dependant deformation which accompanies the application of stress to a material.

Mechanical fatigue is defined as [2] : The process of progressive localised permanent structural change occurring in a material subjected to conditions which produce fluctuating [cyclic] stresses and strains at some point or points and which may culminate in cracks or complete fracture after a sufficient number of fluctuations [cycles].

Material ageing in terms of this study is defined as : Loss of measured strength with time due to prolonged exposure to chemical or electromagnetic radiation ageing mediums.

The review is primarily concerned with the mechanical properties of aramid yarns and considers other strength member materials and potential strength member materials for the purposes of comparison with aramid materials.

Throughout this work, the term decitex is the chosen unit of linear density, and is defined as [3] : The mass in grams of ten thousand metres of yarn.

2.1 The History of Aramid Materials

The first synthetic polymer aramid fibres were produced in 1965 resulting from research work by DuPont scientists in the USA [5]. The first aramid product was launched during the early 1970's under the brand name "DuPont Kevlar 29". By the 1980's DuPont's range of products had grown into a family of aramid materials including high modulus "Kevlar 49" yarn and "Nomex" tape. By the 1980's competition in the form of Akzo Fibres Type 1055 "Twaron" aramid yarns offered a direct alternative to Kevlar 49 yarns.

The 1990's has proved to be a period of quality and traceability awareness within the aramid industry through ISO 9002 accreditation. Individual bobbins of Kevlar 49 can be traced to source through computerised labelling. A bobbin of aramid is defined as [3] : The smallest production unit of yarn on cylindrical cardboard tube.

The early nineties has witnessed an increase in worldwide aramid manufacturing capacity, and aramid manufacturer competition leading to improved aramid availability and falling prices. The future promises to offer specialised tailored aramid products such as Twaron Type 1111, a new yarn designed to give optimum cost performance in optical communication cables.

2.2 The Chemistry of Aramid Materials

Aramid consists of long molecular chains produced from the synthetic polymer polyparaphenylene terepthalate [7]. The molecular chains are highly orientated in the along fibre (parallel to the length of the fibre) direction, with strong interchain bonding in the along fibre direction. Each molecular cluster consists of six carbon atoms around which are bonded oxygen and nitrogen atoms. Thousands of molecular clusters link to form macromolecules. The result is a yarn material five times stronger in terms of strength to weight ratio than steel. The presence of benzene rings ensures thermal stability up to the decomposition temperature of approximately 450°C. The Young's modulus of aramid increases with decreasing temperature and has been used in telecommunication cable applications at temperatures below -60°C without problems such as embrittlement.

2.3 The Manufacture of Aramid Materials

The naturally yellow base polymer powder required for aramid production is produced by polymerization of TDC and PPD monomers with an MNP and calcium chloride solvent. Coagulation of monomers in solvent takes place before the solvent is extracted for reuse. The base polymer powder is dissolved in a very strong sulphuric acid solution. At this point in the production process the main difference in production methods between manufacturers occurs. The Akzo method involves pushing pure crystals of sulphuric acid into the reaction vessel with separate water addition to dissolve the base polymer. The DuPont method involves control and metering of the strong sulphuric acid solution to dissolve the base polymer.

The dissolved polymer is spun by extrusion through a metal nozzle. It is the size of the holes in the nozzle that play an important role in controlling the final diameter of individual fibres. The number of holes dictates the number of individual fibres that form the finished yarn. Acid solvent and water are removed from the spun fibres resulting in fibre diameter reduction and densification. At this stage the acidic fibres are neutralised with sodium hydroxide and washed in clean water *(figure 1)*. Upon drying the adsorbed equilibrium moisture content falls to between three and five percent by weight.

The equilibrium moisture content of aramid will fall if initially wet or rise if initially dry to a constant three to five percent within 24 hours depending on ambient temperature and humidity conditions [3]. Akzo Twaron Type 1055 (1610 dtex) and DuPont Kevlar 49 (1580 dtex) consist of one thousand similar aramid fibres with a mean diameter of 12 μm [8,9].

Depending on grade of product, the yarn is annealed by tensioning at an elevated temperature to further align the molecular chains and convert the yarn from an intermediate to a high modulus type. This is the method used to produce Kevlar 49 from Kevlar 29 yarn.

The yarn is sprayed with a spin finish to reduce electrostatic charging and frictional wear over yarn guides. The finish is defined as [3] : Mixture or emulsion, consisting mainly of oils, which is applied to the fibre surface, mainly to reduce friction and improve processing. The yarn is wound onto cardboard tubes before batch testing and certification.

The first aramid stranding machines were adapted from textile applications. During the 1980's purpose built aramid stranding machines with sophisticated tensioning and matt chrome eyes and pulleys have been developed, machines such as the Tensor machine developed in conjunction with DuPont in North America. Recent work by Akzo has advanced the understanding of aramid stranding where the cable stranding process is restricted by bobbin stability. The maximum speed of bobbin rotation (MSBR) in meters per second is determined by the equation [6]:

$$\mathbf{MSBR = 200/(M \times R_g)^{1/2}} \qquad \mathbf{(2.1)}$$

where **M** is the bobbin weight in kilograms, and $\mathbf{R_g}$ is the radius of gyration in meters, and is the distance between the centre of the bobbin and the centre of the strander [6]. A merge is defined as [3] : The identification code assigned to a specific product. Each merge is irrevocably tied to its own specific production process settings and quality control parameters.

2.4 Properties of Aramid Materials

The introduction of aramid materials as strength members offered an alternative to metallic strength members in communication cables. A big advantage was that truly non-metallic cables could be produced offering zero lightning susceptibility and other electromagnetic advantages. A summary of the properties and advantages of aramid is offered by the manufacturers, and is given below [3,7] :

* Aramid combines high tensile strength with low weight (high Tenacity), and also has a high Young's modulus . Tenacity is defined by DuPont as [3] : Tensile breaking strength of yarn (N) divided by its linear density, mass (**m**) per unit length (**l**) expressed in N/dtex.

$$\begin{aligned} \textbf{Tenacity} &= \mathbf{F/(linear\ density)} = \mathbf{F/(m/l)} \\ &= \mathbf{F/A\rho} = \mathbf{UTS/\rho} \qquad (2.2) \end{aligned}$$

  where **F** is the tensile breaking force of the yarn, **A** is the cross sectional area of the yarn fibres, **UTS** is the ultimate tensile strength and ρ is the density. However it is generally more convenient to use the material tensile strength based on manufacturers fibre area data. The maximum possible tensile strength for Kevlar 49 or Twaron Type 1055 materials is typically 3070 MPa. According to DuPont the tenacity of aramid is greater than rayon, nylon or polyester yarns [3].

a. Aramid offers high thermal and dimensional stability, and is a flame resistant low smoke material.

b. Aramid has good dielectric properties.

c. Aramid has a low elongation at break.

d. Good chemical resistance.

e. Aramid offers good fatigue, creep and wear resistance.

2.5 Academic Literature Study

Since the introduction of aramid into applications which exploit some or all of the above material properties doubts have been expressed regarding some of the long term properties of aramid materials. Such doubts have prompted government agencies such as the Lawrence Livermore Institute in the USA and the former Royal Atomic and Radar Development Establishment in the UK to investigate the material properties of aramid.

2.5.1 Aramid Material Variation

Bobbin to bobbin variation in the physical and mechanical properties of single aramid fibres has been observed [10,11]. Linear density, fibre diameter and material density have been shown to vary from bobbin to bobbin. The variation in tensile strength of individual fibres affects lifetimes in creep rupture tests [12] and the strongest fibres are known to last an order of magnitude longer than the weakest fibres in creep rupture tests.

Size effects in mechanical testing of aramid well below the glass transition temperature (**Tg**) generally apply whereby longer lengths (long gauge lengths) of yarn fail at lower mechanical stresses than short lengths (short gauge lengths). The tensile strength is not simply the sum of the breaking load of the individual fibres, as the larger the testing sample the greater the chance of including larger flaws which act as failure sites during testing. An exception to this principle is that the individual aramid fibres with the smallest diameters possess the highest tensile strengths [13]. The fibres with the smallest diameters are denser and the molecules better aligned. Young's modulus also decreases with increased fibre diameter. For elastic conditions the Young's modulus (**E**) for yarn type materials is defined :

$$\mathbf{E = stress/strain = (F/A)/(e/l)} \qquad \textbf{(2.3a)}$$

The specific modulus ($\mathbf{E_s}$) may be defined as :

$$\mathbf{E_s = E/\rho} \qquad \textbf{(2.3b)}$$

For linear elastic conditions, up to the point of fracture, then :

$$\mathbf{E_s = Tenacity/(e/l) = (UTS/\rho)/(e/l)}$$
$$\mathbf{= E/\rho} \qquad \textbf{(2.3c)}$$

where **F** is the applied force, **A** is the total cumulative cross sectional area of the individual fibres, **e** is the linear extension, **l** is the original length, **UTS** is the tensile strength and ρ is the density. The cross sectional area can be derived from material density and linear density in grams per meter :

$$\mathbf{A = (linear\ density) \times (1/material\ density)} \qquad \textbf{(2.4a)}$$

or in terms of units :

$$\mathbf{A = m^2 = (g\ m^{-1}) \times (m^3\ g^{-1})} \qquad \textbf{(2.4b)}$$

2.5.2 Aramid Creep Observations and Theory

Creep in aramid yarns is known to follow a logarithmic time dependence over nine creep decades (five years) [14]. Depending on the source it is claimed that most or all of the creep is recoverable [14]. Wetting of aramid under creep testing gives rise to an initial increase in log creep rate followed by a return to the original dry log creep rate [14]. It is not known whether the additional small strain due to wetting is reversible upon drying. The creep mechanism responsible for creep in aramid is claimed to be molecular chain scission by breakage of carbon-nitrogen bonds in PPTA molecules *(figure 2)* [15,16]. Breakage of the same carbon-nitrogen bonds may also be produced by photodegradation or thermal activation (heating). Photodegradation is expressed as [13] :

$$\sigma_b/\sigma_o = 1 - ((\tanh (r/t))/(r/t)) \qquad \textbf{(2.5)}$$

where σ_b is breaking strength after time **t**, σ_o is the initial breaking strength and **r** is the degradation constant.

The carbon-nitrogen bond represents the weakest link in the aramid chain structure and must be broken by thermal activation for creep to occur in a creep test, or mechanical failure to occur in a tensile test. The activation energy for aramid material has been measured as 3.35×10^5 J mol^{-1}, and is also subject to variation from one bobbin to another [16]. The temperature dependence of the creep rate (c_s) in aramid materials follows the Arrhenius relationship [17], and is generally expressed as [1] :

$$c_s = K \sigma^n e^{-H/RT} \tag{2.6}$$

where **K** is the scaling constant, σ is the engineering stress, **n** is a material constant, **H** is the creep activation energy, **R** is the universal gas constant and **T** is the absolute temperature. It has been demonstrated that changes in aramid creep rates with applied stress fit an equation of this form [31].

Tensile failure in testing times of only a few seconds occurs at much less than the theoretical maximum carbon-nitrogen bond energy [18]. The log creep rates of high modulus aramid materials are lower than other polymeric materials such as nylon, polyester and Kevlar 29. High modulus aramid yarns posses log creep rates of typically less than 0.02 percent length increase per decade of time (%/dec) at a loading of 50% of their breaking strength. Low modulus aramid materials typically possess log creep rates of 0.05 %/dec under the same conditions. The breaking strength of yarn material may be specified either in terms of load or tenacity at break.

Creep testing may be based on UTS data or load at specified elongation data (LASE). The term LASE is defined as : Average load supported by a yarn before specified elongation [or strain] is reached.

2.5.3 Weibull Theory

Weibull statistics can be applied to aramid and UHMWPE tensile and other test data since the data follows the Weibull distribution given by [19,20] :

$$\mathbf{ln\ ln\ (1/1\text{-}Pf) = m_w\ ln\ (\sigma_f - \sigma_u) - m_c\ ln\ \sigma_n} \qquad \mathbf{(2.7)}$$

where the probability of failure (**Pf**) is given by :

$$\mathbf{Pf = n_t/N + 1} \qquad \mathbf{(2.8)}$$

where $\mathbf{m_w}$ is the shape parameter, $\mathbf{m_c}$ is a constant, σ_f is the measured sample failure stress, σ_u is the threshold failure stress, σ_n is the normalising scale parameter, $\mathbf{n_t}$ is n^{th} test specimen and **N** is the total number of test specimens.

The shape parameter has been shown to remain constant with temperature changes below the glass transition temperature. The scale parameter varies inversely with temperature [16].

2.5.4 Fatigue Properties of Aramid

The fatigue properties of aramid are very good, where composite sample failures have occurred without crack growth in aramid fibres. Failure has been by delamination of aramid fibres and matrix, and plasticisation of the matrix. Internal heating effects with thermal decomposition have been observed in fatigue tests at frequencies above 10 Hz. Tests on ropes that have been subjected to fatigue cycling have identified mechanical abrasion as a source of damage and strength loss by failure initiated at fibril sites [21].

Suggested ways of reducing the effects of abrasion are to lubricate or to rigidly bond fibres together so that no relative movement can occur. Twisting of aramid yarn reduces the strength reducing effects of abrasion by allowing broken fibres twisted into the body of unbroken fibres to contribute tensile strength due to the effects of fibre to fibre friction. A twist is applied as a calculated twist multiplier, and a twist multiplier (TM) of 1.1 gives the highest tensile strength values, and is calculated in the following form :

$$\mathbf{TM = TW \times (linear\ density)^{1/2}/3000} \qquad \mathbf{(2.9)}$$

where **TW** is the twist in turns per metre.

2.5.5 Impurities and Decomposition of Aramid

Impurities and imperfections have been identified in aramid yarns. Ashing followed by optical spectrometry has revealed the presence over one percent impurities by weight in Kevlar 49 [22], including sulphur compounds, aluminium, iron, silicon, chlorine, calcium and potassium compounds. The impurities are concentrated at the centre of aramid fibres within zones of hoop stress. The hoop stresses and impurity distribution are a product of the densification and fibre diameter reduction that takes place during manufacture. Microvoids within fibres have also been identified.

Cook and Howard [23] reviewed the chemical and physical properties of Kevlar 49. Where Kevlar 49 generally offers good chemical resistance, the unaged tensile strength is only slightly influenced by micron size defects. Upon ageing the microvoid defects allow the ingress of hostile soluble ions which increases the chain scission rate destroying lateral crystalline order. Poor bleach (alkali) resistance and strength loss due to ultra violet radiation induced chain scission have been identified as drawbacks to aramid.

Aramid has excellent solvent resistance and good thermal stability (compared with other polymers) due to the presence of benzene rings in the PPTA molecule. The coefficient of thermal expansion is small and negative. Shortening upon heating is accompanied by an increase in fibre diameter. The longitudinal coefficient of thermal expansion is -2×10^{-6} °C^{-1} between 0°C and 100°C and -4×10^{-6} °C^{-1} between 100°C and 200°C. The perpendicular coefficient of thermal expansion is 59×10^{-6} °C^{-1} between 0°C and 100°C [3].

Oxygen deficient gas analysis of combustion (ashing) products is given in *table 1.* The heat of combustion is 34.8×10^{6} J Kg^{-1} [3].

2.6 History and Properties of Ultra High Molecular Weight Polyethylene Yarn

UHMWPE was first was produced in 1979 by DSM High Performance Fibres, Holland, using a patented gel spinning process. Since then the material has been developed by DSM and the Toyobo company of Japan. UHMWPE is manufactured under licence in the USA by the Allied Corporation under the brand names Spectra A and Spectra B. The study material Dyneema SK65 (equivalent to Spectra B) is a development of the first commercial grade of UHMWPE Dyneema SK60 (equivalent to Spectra A) [24]. However only DSM Dyneema products are available in Europe.

UHMWPE differs from ordinary polyethylene materials in that the molecules are much more highly orientated (more than 95% in the axial along fibre direction) and more crystalline (more than 70% compared with less than 60% for ordinary polyethylenes). The mechanical performance advantages of UHMWPE are similar to those of aramid except that creep performance and maximum working temperature are identified as being inferior to those of aramid materials. Chemical resistance particularly ultra violet radiation resistance is claimed to be better than aramid. UHMWPE is claimed to be stronger than aramid material by weight. This claim is due primarily to the low material density of UHMWPE, which is 0.97 g cm^3 compared with 1.45 g cm^3 for high modulus aramid materials [25].

The similarity of a number of mechanical properties to aramid yarn suggested UHMWPE material as a potential axial reinforcement for communication cables, but so far no cable manufacturer has reported using this material. The tensile failure mechanism, like that of aramid, involves longitudinal splitting of fibres. Similarly size effects do give rise to variation in results in mechanical tests. Also, like aramid, variation in the material leads to modification of mechanical properties, such as larger diameter fibres having lower tensile strengths than fibres with smaller diameters. This is due to thicker fibres containing more kink bands (zones of tangential fibre shearing) than thinner fibres [26].

Weibull modelling is carried out even though as data from UHMWPE mechanical tests do not precisely follow the Weibull distribution [18]. Failure is initiated at kink band sites but one important mechanical property of UHMWPE is that unlike aramid there are no longitudinal size effects. This phenomenon is attributed to a very short period of flaw distribution (concentric kink bands), and that flaws are of a single type and possibly size. Chain slippage has been identified as the most likely creep mechanism in UHMWPE *(figure 3)*.

2.7 The Principle and Practice of Yarn Jointing

It is current practice to leave a small quantity of aramid on each cardboard centre after the last cable from that bobbin has been produced. It is essential that bobbins are not allowed to run out as aramid stranding machines utilise sophisticated electronic tension control systems, the free end would come off the guides and become entangled in the moving parts and there may be up to 48 bobbins on a strander carriage where it would not be desirable for each bobbin to end one at a time. The result is that each bobbin used remains with typically 100 m to 300 m or more of unused yarn left on the cardboard centre.

Without a jointing procedure the remaining yarn is only suitable for disposal, as no re-cycling process exists. It is therefore desirable on cost and environmental grounds to join and rewind the yarn for use in communication cables. Knotting of yarn is undesirable as knots posses only 30% of the tensile strength of virgin material. The use of adhesives is not desirable due to material compatibility issues and the risk of sticking successive turns of aramid together during rewinding. The method of jointing recommended by aramid manufacturers is air splicing and is considered further in this thesis.

Yarn jointing by the air splicing process is a pneumatic method of joining industrial continuous fibre yarns. The method used in this study is the Enka Technica double splice method [27], which has the advantage of joining yarns together without leaving protruding ends which are difficult to process.

Protruding ends catch in dies and other tooling and can protrude out of metallic tape overlaps.

The equipment consists of a hand held gun connected to a compressed air supply. Contained within the gun are timed valve mechanisms, and an air chamber situated between two sets of cemented carbide knives. The timed valve mechanisms are controlled by a push button trigger mechanism. The principle of air splice jointing is that currents of compressed air within a non pressurised chamber are introduced into the chamber at the chamber centre. The currents are divided into two along the long axis direction of the two yarn ends. The air currents within the chamber contra-rotate with "S" and "Z" twist such that the yarn fibres are split into twisted left and right side bundles. The yarn fibres follow the motion of the air currents.

The left and right side fibres from the two ends of yarn intermingle with "S" and "Z" twist in the contra-rotating air currents and so become entangled without the need for adhesives or knotting. The result is a mechanical joint which can be formed using aramid, glass, polyester or nylon material yarn. The yarns can be jointed with mean predicted tensile strengths of 95% of the intrinsic material strength of unjointed material. The chamber size dimensions must be matched to the fibre count for maximum splice strength to be realised.

Upon pulling the gun trigger, the cemented carbide knives very quickly snap across each other and cut the ends of the yarn so that no excess yarn protrudes from the air chamber. A brief pause after cutting allows the cut ends to relax before the timed air blast begins. The timed air blast takes 0.2 s to 2.0 s depending on timer valve setting. The result is a double splice formed by the action of symmetrical turbulent air currents flowing parallel to the long axis of the two yarn ends. One half of the double splice is formed with an "S" twist and the other half with a "Z" twist.

The splice performance affecting parameters are listed below :

a. Yarn Young's modulus.

b. Yarn twist.

c. Yarn linear density and yarn fibre cross sectional area.

d. Surface finish and coefficient of friction. Smooth surface coatings such as aramid spin finishes reduce splice strength by reducing the mechanical friction which holds the splice together.

e. Yarn condition and conditioning (drawn or undrawn).

f. Moisture content.

g. Air pressure.

h. Air blast duration

2.8 Statistical Analysis

Suitable statistical analysis of tensile test results has been shown to consist of minimum, maximum and average results with the standard deviations for samples taken from the total population. The literature investigation has shown tensile results to be suitable for testing using the Students t-test for 24 degrees of freedom, for a sample size of twenty five [28,29]. Hypothesis **H0** and **H1** are constructed as appropriate.

3.0 EXPERIMENTAL METHODS

The experimental work was divided into five parts, tensile testing methods, creep testing methods, fatigue testing methods, ageing and weathering test methods and the aramid yarn jointing procedure. The first stage involved developing tensile test methods to provide test parameters for the subsequent creep, fatigue and ageing tests. All testing was then carried out at Pirelli Cables, Newport, Gwent, except cable tensile and creep testing which was carried out by Akzo Fibers, Arnhem, Holland.

3.1 Tensile Testing Methods

All tensile testing work was carried out on an Instron model 4502 tensile testing machine. The general yarn tensile test method was developed to give accurate and repeatable breaking load information. The material yarn LASE test method required the modification of the initial yarn tensile test to allow the application of a clip on extensometer. The extensometer enabled the collection of accurate load against strain (LASE) data which was subsequently used as the basis of material yarn creep and fatigue testing. The cable LASE test method was an adaptation of the yarn tensile test methods to suit finished cable applications.

Instron 4502 Series IX software permitted automatic data collection and some statistical analysis of breaking load and LASE data. Data was transferred from Instron 4502 printouts to a PlanPerfect spreadsheet.

3.1.1 General Yarn Tensile Test Method

All yarn materials were conditioned at 23°C ± 3°C and 60% R.H. for a minimum of 24 h before tensile testing to allow the moisture content to reach equilibrium. The conditions were those in which the Instron testing machine was stored.

The general yarn tensile test method was developed to provide tensile breaking load data for up to 100 consecutive test samples. The method used 60 mm diameter helically grooved aluminium alloy capstans, with yarn clamping by 40 mm long aluminium alloy flat plates attached to the capstan bodies. The gauge length was 500 mm, and was the distance between the two capstan centres, the gauge length was an approximation as some movement of yarn around the capstans occurred. The testing speed was 40 mm/min *(figure 4)*.

Yarn was installed into the test equipment and tensile tested to break by the following procedure :

a. Cut approximately 1 m of yarn from the bobbin.

b. Wrap one end of the yarn sample around the top clamp and tighten the three allen key bolts by hand.

c. Pull the yarn sample taught and wrap the yarn once around the top capstan.

d. Keep the yarn taught and wrap the yarn once around the bottom capstan.

e. Wrap the end of the taught yarn around the bottom clamp and tighten the allen key bolts by hand.

f. Tighten the allen key bolts using a 3 mm allen key.

g. Perform the tensile test on the yarn only if the yarn is free from fluffing and snags. If the yarn is visually fluffed or snagged discard the yarn sample and repeat the procedure.

h. Perform tensile test to automatic test end.

i. loosen the clamp plates and remove the failed test sample.

3.1.2 Material Yarn LASE Test Method

The material yarn LASE test method was developed to provide accurate load versus strain data for yarn materials. The yarn conditioning, and the basic tensile test configuration was the same as the general yarn tensile test method. The difference between the two tensile test methods lies in the use of a clip on strain gauge *(figure 5)*. The testing speed was the same as the general yarn tensile test at 40 mm/min.

Additional yarn preparation was required to facilitate the fitting of the clip on strain gauge. Rigid heat shrink polymer tubes were applied to the smooth yarn surface so as to avoid slippage of the strain gauge blades over the smooth yarn surface. The method of yarn LASE measurement is given below :

a. Slide two rigid 20 mm long rigid polymer tubes over one end of the yarn and move the tubes into the centre of the sample leaving a 40 mm inside spacing between the two tubes.

b. Shrink the rigid polymer tubes down onto the yarn with a hot air gun.

c. Install the yarn into the tensile testing machine as stated, with the rigid heat shrink tubes situated at the centre of the gauge length region.

d. Clip the extensometer to the yarn using rubber "O" rings.

e. Zero the clip on extensometer.

f. Tensile test to specified test end load.

3.1.3 Cable LASE Testing

A LASE test was developed to test the same specially manufactured cable sample lengths. The cable samples were similar to the commercial product except that no hot melt adhesive was applied to the aramid yarn during manufacture. Cable samples were manufactured without hot melt adhesive or any other coating as smooth coatings shear under load, and the yarn slips out of the epoxy resin pot. Attempts to remove aramid coatings proved unsuccessful and resulted in aramid strength reduction.

The cable LASE methods utilised an Inductive Displacement Sensor (IDS) extensometer and a 700 mm length of aramid stranded finished cable, which gave an IDS gauge length of 500 mm. The testing speed was 70 mm/min, and 60 mm of both cable ends were potted in epoxy resin (Araldite MY 753, hardener HY 951). Aramid and GRP rod strength member materials were potted in epoxy resin. An unavoidable difference in gauge length and testing speed between the cable and yarn LASE tests occured. It is believed from tensile tests on aramid at 70 mm/min that the effects of such differences in testing regimes are not significant. The cable sheath and cable core were cut off short of the epoxy potting. Flat faces were machined onto the epoxy resin ends to allow grip in the tensile testing machine 12 mm wide jaws *(figures 6 & 7)*. The procedure for tensile LASE testing of cable is given below. The IDS data was used to produce LASE plots for cable creep test configuration. An IDS gauge length of 500 mm gave a displacement accuracy of ± 5 μm at 20°C ± 2°C and 65% R.H. The cable IDS LASE method was as follows :

a. Clamp both ends of the prepared cable sample into the Instron 4502 tensile testing machine jaws.

b. Clip the IDS onto the central portion of the cable sheath using the two IDS clamps.

c. Zero the IDS extensometer reading.

d. Begin tensile testing until the sample fails and the test stops automatically.

e. Return the crosshead and unclamp the cable test specimen.

f. Repeat the LASE test on the central GRP rod only.

3.2 Creep Testing Methods

Two different but similar creep testing methods were devised. The first requirement was for a comparative laboratory creep test applicable to non metallic yarn type materials. It was a requirement that the yarn creep test measurements should be free from end effects where the stress concentration effects caused by having terminations present within the measurement gauge length, and that the test could be enlarged at any time to allow for the inclusion of new yarn material products.

The second requirement was for a laboratory finished cable creep test to yield creep information that could be compared with creep information from the material yarn creep tests.

3.2.1 Material Yarn Creep Testing

Conventional proprietary creep testing equipment is designed to test short dumbbells, bars of metal or other solid materials. Data collection in such systems is usually by multiple displacement sensors coupled to a personal computer through a data collection interface card. Such methods are unsuitable for creep testing of continuous yarn materials as yarn samples lack rigidity and require support and suitable terminations.

The most suitable arrangement was found to be 10, 400 mm gauge length test samples. Each sample consisted of a loop top and bottom within a plastic bobbin *(figure 8)*. The loops were formed by trapping the free ends of the yarn into rigid heat shrink polymer tubes and bonding the yarn ends with cyanoacrylate contact adhesive. The smooth plastic bobbins greatly reduced the stress concentration effect that occured at the ends of the creep test samples. No premature failure at the terminations occurred throughout the period of testing. Knots in aramid and UHMWPE possess a tensile strength of typically 30% of the strength of unknotted material and lead to premature creep test sample failure at a knot.

The creep test loadings for each of the five yarn materials were chosen on the basis of the material yarn LASE test results. The loadings used represent the loads required to produce an initial strain of 0.5% which is a typical maximum value a cable may see in service or during installation.

Both ends of the creep test specimens were identical in construction. The top bobbin was attached to a steel frame through the plastic bobbin by steel wire. The bottom loop was attached to the appropriate creep load by a second steel wire. Fixed onto the yarn were heat shrink tubes containing a rigid steel wire formed into a "V" shape that acted as the locating notch for the tip of the mechanical contact measuring probe *(figure 9)*.

The measuring equipment consisted of a Mitutoyo Heightmatic 600 vertical height gauge measuring system with touch probe sensor and DP-1 HS Digimatic Mini

Processor *(figure 10)*. The digital readout scale smallest division was 1 μm, and the equipment accuracy of measurement was $\pm$ 2.5 μm. The method of collecting and recording material yarn creep test measurements is given below :

a. Locate the creep test specimen into the Instron 4502 frame by hanging the top loop of the creep test specimen from the load cell fixing. Stand the sample in the frame for three minutes to allow for the elimination of any differences in temperature and humidity that may exist between the creep test frame storage area and the Instron frame area.

b. Adjust the position of the crosshead until the bottom of the creep sample load is approximately 10 mm above the Instron 4502 platform.

c. Rotate the creep test sample in the load frame until the "V" notch contact points are aligned perpendicular to the Mitutoyo height gauge probe.

d. Stop the creep test sample from rotating in the Instron 4502 frame by placing a metal "stop" in front of the creep test sample load.

e. Lower the probe to the lower measurement position and move the height gauge on the engineers bench until the probe fits neatly into the lower "V" notch.

f. Switch the height gauge to position "C" and raise the probe to the upper measurement position before fitting the probe into the upper "V" notch.

g. If the probe does not align properly with the upper "V" notch adjust the levelling of the engineers bench and repeat the probe alignment procedure.

h. Raise the probe to within 10 mm of the upper "V" notch position, then guide the probe up past the upper "V" notch using the fine adjuster. The height gauge will sound and the digital readout will automatically zero.

j. Lower the probe to within 10 mm of the lower "V" notch position and switch the height gauge to position "H".

k. Using the fine adjuster lower the probe into the lower "V" notch and past the data collection position. The measurement of length will be recorded automatically and printed out by the DP-1 HS Processor as the gauge sounds.

l. Repeat the length measurement procedure until three length measurements agreeing to within $\pm$ 5 μm are achieved. If the three agreeing length measurements are not achieved within ten consecutive length measurements, repeat the probe alignment process, and repeat the data collection process until the three agreeing readings are achieved. The recorded length measurement is the average of the three length measurements agreeing to within $\pm$ 5 μm.

m. Return the sample to the creep test support frame and repeat the alignment and length measurement process for the other nine creep test samples of the same yarn type *(figure 11)*.

n. Transfer the ten mean length measurements from the DP-1 HS printout to Planperfect. Calculate the average length of the ten creep specimens by taking the average of the ten individual sample averages.

o. Repeat the creep sample length measurements at logarithmic time intervals.

3.2.2 Cable Creep Testing

Cable creep tests were performed using the IDS (Inductive Displacement Sensor) method. The IDS like the clip on extensometer is an electrical device mechanically attached to the specimen which measures axial elongation and so is a suitable device for measuring cable extension. The elongation data is then converted into percentage strain by the personal computer attached sensor via a data collection interface card to the IDS. Data collection is automatic over the period of testing. A cable end epoxy resin potting technique similar to that used for cable LASE test samples was used to prepare cable samples for the cable creep test.

Untwisted aramid material breaks without any yielding at a strain of 2%, and thus the load required to strain the yarn by 0.5% is one quarter of the cable tensile breaking load (the GRP rod did not break during the tensile tests), if the strength contribution of the central GRP rod is deducted. The GRP rod fails in tension at a strain greater than two percent. The other materials in the cable such as low density polyethylene sheath are not significant tensile strength contributing materials.

The IDS cable LASE test results indicate that cable breaking strains were greater than 2%, because the cable samples required an initial strain before full aramid tensile strength contribution was realised. This cable tensile feature results from a need to remove aramid slackness before aramid strain can occur, consequently aramid strain was always less than cable strain. A combination of IDS cable LASE and breaking load data was used to determine the appropriate load required to achieve an aramid strain of 0.5% within cable samples. The load is referred to in the method as the cable creep test loading, and was 6.6 Kg. The cable creep test method for single cable creep test samples was as follows *(figure 12)*:

a. Suspend the creep test sample from the creep test frame by the top pulling eye.

b. Clamp the IDS to the middle portion of the cable creep test sample sheath.

c. Zero the IDS displacement reading and begin continuous data collection.

d. Gently suspend the creep test load from the lower pulling eye.

e. Allow automatic data collection to take place until the specified end of test.

3.3 Fatigue Testing Methods

Suspended aerial cables on undergo "aeolian vibration" when subjected to gusts of wind. The frequency of wind induced resonant vibration is typically between 20 Hz and 120 Hz at low mechanical strains. Galloping may occur due to strong cross winds and is a low frequency high amplitude vertical movement of cable catenaries. The material yarn fatigue tests were devised within limiting machine constraints to simulate the effects of a mechanical cycling action on yarn materials and yarn terminations of a type used in aerial communication cables. In practice the fatigue tests were limited by the ability of the fatigue test equipment to achieve high testing frequencies whilst maintaining peak loadings. The aim of the yarn fatigue tests was identify the strength reduction modes that operate in peripheral strength members subjected to fatigue cycling whilst being constrained by clamps and other stress concentrators.

3.3.1 Material Yarn Fatigue Testing

A programme of fatigue testing was carried out using the Instron 4502 tensometer load strain function. The load strain function uses feedback to control the cyclic motion of the crosshead where the magnitude of the electrical signal to the driving motors controlloing the position of the machine crosshead is dependant on load detected by the load cell. This allows a conventional fatigue test to be performed on the yarn using the same capstans as those used for yarn support in the yarn tensile tests. The configuration of the fatigue tests was the same as that used in the tensile test except for the control of the crosshead movement *(figure 13)*.

The LASE data used to configure the creep tests also formed the basis of the fatigue tests. The machine was operated in load control mode, where the maximum cyclic loading for each material was the load that produced an initial 0.5% strain. The load control mode selected was sinusoidal with a minimum value of zero initial strain (0 N), an average value of load at 0.25% initial strain and a maximum value of load at 0.5% initial strain *(figure 14)*.

Testing frequencies used were 1, 2 or 3 hertz depending on machine capability. It is recognised that low fatigue test frequencies below 10 Hz do not give rise to thermal decomposition of polymeric materials by internal heating. Above 10 Hz frequency there is a chance of thermal decomposition due to the inability of frictional heat generated to be dissipated into the surrounding environment, (polymeric materials such as aramid and UHMWPE are known to suffer from thermal decomposition during testing). Thermal decomposition is a product of the poor thermal conductivity of polymers, aramid material does not soften below the glass transition temperature, polyethylene however may soften .

The testing procedure was to test six samples of each of the five study material types together at each of 1, 10, 100, 1,000, 10,000, 100,000 and 1,000,000 cycles. A total of 36 fatigue test samples per material were tested. Sample selection was made by removing any fluffed or discoloured yarn, winding yarn off the sample bobbin and cutting with aramid scissors. The Instron 4502 was able to automatically stop the test at the predetermined test end and count the number of fatigue cycles to failure should premature failure occur. The fatigue test method is given below :

a. Group six yarn fatigue test specimens together and install them into the Instron 4502 capstans as described in the general yarn tensile test method. The fatigue test method uses the capstan grips and a gauge length of 500 mm.

b. Set the load strain controller to the sinusoidal control and input the require number of test cycles.

c. Set the maximum load to 6x the load corresponding to an initial 0.5% strain for the selected material type.

d. Set the mean load to 3x the load corresponding to an initial 0.5% strain for the selected material type. The minimum load will then automatically be 0 N corresponding to zero strain.

e. Set the test number of cycles to the desired test value.

f. "**Enable**" the load strain controller.

g. "**Start**" the test and adjust the gain of the PID amplifiers to give a smooth function that just attains maximum load.

h. "**Stop**" the test and replace the sample yarns.

i. "**Start**" the test and allow the test to continue to the pre-determined end of test.

j. At test end remove the surviving test yarns from the capstan grips.

k. Separate the six yarn roving into individual yarns.

l. Tensile test the six yarns individually in accordance with the general yarn tensile test method.

3.4 Ageing and Weathering Test Methods

The ageing work is intended to give an indication of the chances of peripheral strength member strength loss due to exposure to ageing media. The implications are that aerial cable service life will be shortened if strength member strength reduction occurs where no sheath or other repair is carried out. The implications for duct cables are that loss of peripheral strength member strength will make re-installation of cables at a later date impossible due to the mechanical tensile stresses and resultant strains involved.

The ageing tests consisted of subjecting Dupont Kevlar 49 Type 989 (1580 dtex), Akzo Twaron Type 1055 (1610 dtex) and DSM Dyneema SK65 (1760 dtex) yarns to chemical, thermal and electromagnetic ageing media. The ageing mediums selected were a comprehensive selection of those that a communication cable strength members could be immersed in after installation.

Under normal circumstances cables will be protected from the actions of ageing media by the cable sheath, waterproof terminations, joint boxes and a host of heat shrink and push on end caps, sleeves and glands. In practise cables may be damaged during transportation or installation, aerial cables may be subject to additional sheath damage by the action of birds or shotgun pellets. Duct cables may be subject to additional damage due to rodent and termite attack or scraping and crushing during and after installation.

Prior to testing of aged yarn samples a comprehensive programme of tensile and LASE testing of unaged materials was carried out to determine the breaking loads and LASE performance of unaged materials. These results were used as the benchmarks for the applied tensile tests and testing conditions. The unaged results are considered here as the 100% strength criteria, and are used as the basis of strength loss calculations in the results section.

3.4.1 Hydrochloric Acid Ageing

Ageing of the three material yarn types was carried out as shown in *figure 15*, the material chemical ageing schematic. For each of the material types one test bobbin of yarn was wound off the commercial bobbin by using electrical rewind equipment. For each material type one test bobbin was wound off for each of the individual ageing tests. Testing was carried out using 0.5 molar and 1 molar solutions at 23°C, 50°C and 80°C. Testing was carried out at each temperature and concentration for durations of 24 hours, 100 hours, 500 hours and 1000 hours making a total of 48 rewound hydrochloric acid ageing test sample bobbins. The rewound test bobbins were placed in sealed jars with the ageing solution. The jars were stored in a controlled environment at 23°C or hot box ovens at 50°C and

80°C, depending on designation. The individual hydrochloric acid ageing tests are shown in *table 2*.

Upon predetermined completion of ageing, the test bobbins were removed from the ageing solution and rinsed for 24 hours in clean tap water to remove residual ageing solution. The test bobbins were then dried for 24 hours at 50°C in a hot box oven. Prior to tensile testing all sample bobbins were stored in the tensile testing environment at 23°C and 60% r.h. for 24 hours to allow the moisture content to rise to the equilibrium moisture content. Finally 25 samples from each bobbin were tensile tested in accordance with the general yarn tensile test method.

For each of the surviving yarn samples on bobbins aged at the highest temperature and hydrochloric acid concentration five samples were LASE tested in accordance with the material yarn LASE test method. The hydrochloric acid testing scheme is more comprehensive than the other ageing test schemes as it was intended that these tests should give additional information on concentration and temperature effects.

3.4.2 Sodium Hydroxide Ageing

The same general scheme of ageing as that used for hydrochloric acid was used for ageing of samples in sodium hydroxide except that no ageing was carried out using a 0.5 molar solution, and no ageing was carried out at 50°C. The programme of ageing was carried out at 23°C and 80°C using a 1 molar sodium hydroxide solution, for durations of 24 hours, 100 hours, 500 hours and 1000 hours making a total of 24 rewound sodium hydroxide ageing test bobbin samples. Standard tensile and LASE testing procedures were used on the aged yarn. The individual sodium hydroxide ageing tests and other ageing tests of the same type are shown in *table 3* for clarity.

3.4.3 Detergent Ageing

Detergent ageing was carried out using the same scheme as that used for sodium hydroxide ageing. The detergent solution was a 1% Antarox CO-630 solution. The 1% Antarox solution is a standard detergent solution used within the telecommunications industry and is referenced in British Telecommunications plc (BT) testing specifications.

3.4.4 Saturated Salt Water Ageing

Saturated salt water solution ageing was carried out using an industrial grade of sodium chloride. The solution was prepared by dissolving salt into tap water contained in glass ageing jars until a layer of crystalline salt formed at the base of the ageing jars. Ageing was in accordance with the material chemical ageing scheme and the ageing regime given in *table 3*.

3.4.5 Tap Water Ageing

Tap water ageing was also carried out in accordance with the ageing regime given in *table 3*, and in accordance with the material chemical ageing scheme, except for the tap water rinsing stage which was omitted.

3.4.6 Thermal Ageing

Thermal ageing was carried out as shown in *figure 16* the material thermal ageing schematic, and *table 4* the thermal ageing scheme. Aramid materials were thermally aged at 100°C and 150°C. UHMWPE was aged at 100°C and 125°C. In each case the highest ageing temperatures represent a practical maximum. Above 150°C the vegetable oil spin finish applied to aramid at the time of manufacture decomposes rapidly and is known to induce nausea in personnel subjected to the combustion gases. UHMWPE decomposes above 140°C, the visible signs of decomposition are discolouration from white to a scorched brown burnt appearance accompanied by a total loss of tensile strength.

3.4.9 Ultra Violet Ageing

Ageing was carried out in a standard Accelerated Weathering Tester (AWT) supplied by the Q-Panel Company. Test bobbins were made up of yarn samples wound onto the AWT test panels. The AWT was operated using u.v. "A" type lamps providing ultra violet radiation in the region 315 nm to 400 nm. u.v "A" lamps closely simulate the u.v. radiation of the sun at the surface of the earth. The optical power output of the u.v. lamps closely resembles that of sunlight with an unfiltered Irradiance peak of 0.8 $W/(m^2 nm)$ at 400 nm. The cabinet and test conformed to ASTM Designation : G53-88 : Standard Practice for Operating Light- and Water-Exposure Apparatus (Flourescent u.v.-Condensation Type) for Exposure of Nonmetallic Materials.

The u.v. ageing was divided into 8 hour cycles consisting of 4 hours u.v. irradiation and 4 hours water condensation at 50°C. An example of a u.v. ageing test was the 24 hour ageing test which consisted of 12 hours u.v. irradiation and 12 hours water condensation in 8 hour cycles.

3.4.7 DERV Diesel Oil Ageing

Derv diesel oil ageing was carried out at 23°C only for safety reasons. The testing followed the general material chemical ageing schematic except that each aged test material bobbin was wrapped in absorbent tissue, and placed on absorbent tissue paper to remove excess diesel oil. The second drying stage consisted of heating to 50°C in a ventilated fan assisted hot box oven *(figure 18)*.

3.4.8 Petrol Ageing

Petrol ageing was carried out using premium unleaded petrol at 23°C. The testing scheme was precisely the same as that used for diesel oil ageing.

3.4.9 Outdoor Material Yarn Weathering

Outdoor weathering of Kevlar 49 (1580 dtex) aramid took place on a purpose built Outdoor Weathering Frame (OWF) *(figure 19)*. The frame was constructed from galvanised Dexion™ material in accordance with BS 2782 : Part 5 : 550A : 1981 (ISO 4607-1978) : Methods of Exposure to Natural Weathering.

The standard stipulates that the weathering samples must be at an angle of 45°, facing south, and not occluded by nearby objects or buildings. The test material should also be more than half a meter above the ground so as to avoid rain splash. In contrast to the u.v. ageing, aramid samples were weathered under strain. Aramid samples were attached by loops to the frame at the top and bottom *(figure 20)*. A weight was attached to the lower aramid loop. The weights attached to the aramid were the weights corresponding to an initial 0.5% strain and were the same as the weights used as the basis of material creep and fatigue testing. The EWF was mounted on top of a 3m tall flat topped water tank in Newport, Gwent, South Wales. Test samples were tested on the frame until failure occurred. The criteria for failure was an inability of the aramid yarn to sustain the applied load.

3.5 Aramid Yarn Jointing Procedure

DuPont Kevlar 49 Type 989 (1580 dtex) material yarn was jointed using an air splicing technique. Proprietary Enka Technica Type III air splicing equipment coupled to a factory 0.608 MPa (6 bar) compressed air supply *(figure 21)*. A single 40 mm air spliced joint was made per 400 mm jointed yarn creep test sample. Ten jointed yarn creep test samples were tested in total. One 40 mm joint was made per 500 mm jointed yarn fatigue test sample. 36 jointed yarn fatigue test samples were tested in total prior to tensile testing.

The procedure for making a 40 mm joint in 1580 dtex aramid is given below. 1610 dtex, 3160 dtex and 3220 dtex aramid can also be jointed using the following procedure *(figure 22)*:

a. Set the air blast duration control to setting "8", (A calibration exercise has shown that a setting of "8" on the air blast duration control knob will give joints with the highest achievable UTS).

b. Prepare sufficient 1 m long yarn samples to give the required number of splices when spliced "end to end" (continuous jointing).

c. Take a length of prepared yarn and place it across the splicing gun chamber with a 10 cm length of yarn hanging over the right side of the gun.

d. Pull the short 10 cm length of yarn tight over the air chamber then downwards and backward so that the yarn is tightly gripped by the right side circular yarn grip.

e. Pull the long end of the yarn tight across the splicing chamber and then forward through 90° so that the yarn lies in the left side yarn channel.

f. Pull the long yarn end down into the left side yarn channel until the yarn is gripped firmly under the locking mechanism.

g. Take a second length of yarn and repeat the installation procedure, with the exception that the short 10 cm length should be gripped by the circular grip on the left side of the gun, and the yarn should be pulled over and across the chamber to the right side before being pulled down forward into the right side yarn channel.

h. Pull the splicing gun trigger, and hold the trigger in until the air blast stops automatically.

i. Remove the jointed yarn sample, and discard the cut off ends from beneath the left side and right side circular grips.

j. Repeat the jointing procedure taking the free end of one of the jointed yarn samples as one side of the next joint. Rewind onto a bobbin as required.

4.0 RESULTS

The results are divided into four sections, tensile testing results, creep testing results, jointed aramid results and ageing weathering testing results.

4.1 Tensile Testing Results

The tensile testing results are sub-divided into three sub sections, general yarn tensile test results, material yarn LASE test results and cable LASE test results.

4.1.1 General Yarn Tensile Test Results

One hundred samples of Akzo Twaron Type 1055 (1610 dtex), DuPont Kevlar 49 Type 989 (1580 dtex) and DSM Dyneema SK65 (1760 dtex) material yarns were tensile tested using the general yarn tensile test method. The purpose of the testing was to produce directly comparable UTS results for the materials using the same test and conditions to benchmark the unaged yarns against the test and the test conditions for comparison with tensile test results for aged materials.

The tensile test results are summarised in *table 7*. Ranked tensile test breaking load and breaking stress (UTS) results for Twaron are shown in *figure 23* and results for Kevlar are shown in *figure 24*. The results for both show a profile characterised by the strongest and weakest data points deviating from the linear data profile. The ranked tensile test results for Dyneema are shown in *figure 25*.

The ranked tensile test results for Dyneema show a distribution characterised by data in the upper quartile breaking at loads greater than those predicted by a linear data profile. For the purpose of comparison the ranked tensile test results for the three materials are shown together in *figure 26*. *Figure 26* shows a marked similarity in UTS behaviour between the Twaron and Kevlar materials. *Figures 27, 28 & 29* show grouped tensile test results. *Figure 30* shows the Twaron and Kevlar grouped data on the same plot for the purpose of comparison. *Figure 30* shows not only a marked similarity in the distributions of Twaron and Kevlar but also a tendency to deviate slightly from the normal distribution in the lower UTS groupings. The data groups are given in *table 8*, Twaron and Kevlar use the same group intervals. *Figure 29* shows that the Dyneema distribution is skewed towards the higher UTS groupings and has a bimodal distribution.

Weibull plots of the tensile test results are given in *figures 31, 32 & 33*, where **lnln(1/Probability of Survival Ps)** is plotted against **ln(UTS)**. The slope of the regression is taken as the Weibull shape parameter $\mathbf{m_w}$. The Weibull shape parameters for Twaron, Kevlar and Dyneema are 30.9, 29.0 and 12.2 respectively. *Figure 34* shows the tensile test results in **Breaking Load & Breaking Stress** against **Probability of Failure** form for Twaron, Kevlar and Dyneema.

4.1.2 Material Yarn LASE Test Results

The material yarn LASE test results are shown in graphical form in *figures 35 & 36*, the data includes a pretension to reduce the spread of results. The material yarn LASE test results shown in *table 9* and *figure 36* form the basis of yarn creep and fatigue testing. The LASE performance of Twaron, Kevlar and Dyneema are similar. The LASE performance of Owens Corning OFY 680 was higher than that of the other materials indicating a more rigid material. Plotted on a tenacity basis the high strength per unit weight of aramid is higher than the other materials indicating the material most suited to high strength low weight applications.

4.1.3 Cable LASE Test Results

Cable LASE test results are shown in *figure 37*. The results given in the **Tensile Loading (N)** against **Percentage Cable Strain** plot represent an average of three LASE tests carried out on three samples of cable cut consecutively from a length of finished cable. The cable LASE data is used as the basis of cable creep testing and gives the breakdown of component contributions of the GRP rod central strength member and the peripheral aramid strength members to the overall strength of the cable. The aramid contributed 80% of the tensile strength of the cable after an initial strain required to "bed in" the aramid. Adjustment for bedding in gives a load of 8.8 KN at 0.5% strain. 8.8 KN was the cable creep loading for the cable samples where the GRP rod was **not** potted into the epoxy resin with the aramid strength members.

4.2 Creep Testing Results

The creep testing results are divided into two sections, material yarn creep test results and cable creep test results.

4.2.1 Material Yarn Creep Test Results

The material yarn creep test results are summarised in *table 10*. The material yarn creep data is shown in a **Percentage Creep** against **Test Duration** plot in *figure 38*. The extension shown is percentage increase in sample length due to creep, the initial 0.5% elongation due to loading is not shown.

The results shown in *figure 38* for aramid and glass materials show low percentage elongations due to creep compared with the other materials. The linear creep rate (the creep rate at any instant in time is the slope of the **Percentage Creep** against **Test Duration** plot at the chosen instant), can be seen to progressively decrease with time. The Dyneema results record much more creep than the other material types without the log dependence shown by the other materials.

Figure 39 shows the same material yarn creep data shown on a **Percentage Creep** against **Time (logsec)**. The average slope of each plot represents the material log creep rate in percent elongation per decade of time (%/dec). Log creep rates are shown in *table 11*. The results show the aramid and glass material log creep rates to be low and linear except for the possibility of an increase at the end of the test period. The UHMWPE material results show a much higher log creep rate than the other materials at any time. The Dyneema log creep rate increased as the test progressed, a mean creep rate is recorded for this material. The gauge length dependence of the jointed aramid is evaluated in the jointed aramid material results section 4.4.

Figures 40 shows the material creep test results in **Percentage Elongation** against **Test Duration (hours)** form, where the initial strain due to loading and creep are shown. *Figure 41* shows the material creep test results as **Percentage Elongation** against **Time (logsec)**. A comparison of creep and elongation plots show the effect of the initial 0.5% creep loading on the creep performance of the materials.

4.2.2 Cable Creep Test Results

Cable creep test results are summarised in *table 12*. *Figure 42* show **Percentage Elongation** against **Test Duration (hours)** for the three cable test samples. The initial elongations of the three cable samples show a marked variation. A log dependence is observed, the cable creep behaviour is covered in the Discussion. A plot of **Elongation** against **Time (logsec)** is given in *figure 43*, the plot shows a very similar log creep performance for the three cable samples. Initial data shows a lower elongation than that predicted by the log dependence. *Figures 44 & 45* show average cable creep and log creep test results for the three cable samples.

4.3 Material Yarn Fatigue Test Results

Figure 46 and *table 13* show the fatigue test results for aramid yarn materials. The plot of **Tensile Breaking Load (N)** after fatigue testing against **Number of Fatigue Cycles** sine 0-0.5% yarn strain shows the effect of mechanical abrasion on material strength. Dyneema was least affected by abrasion although some strength reduction was recorded.

The performance of the two unjointed aramid materials was similar but some strength loss was due to the observed effects of mechanical abrasion. Jointed Kevlar 49 and Owens Corning glass yarn failed during the test, the number of cycles at which the samples were unable to sustain the cyclic loading is recorded in *table 13*. The failure mechanisms for the jointed aramid and glass materials were different. Jointed aramid failed by pulling apart of the air spliced joints. The glass yarn failed by extensive breakage of glass fibres in the clamps and around the capstans.

Figure 47 shows the fatigue test results for all yarn materials, the plot highlights two important material features :

a. Firstly the similarity in behaviour of the two brands of unjointed aramid.

b. Secondly that the tensile strength of jointed aramid increases until mechanical abrasion of the aramid at the clamps and around the capstans (as seen in unjointed aramid fatigue tests) gives rise to failure of component fibres.

4.4 Jointed Aramid Materials Results

A summary of jointed aramid results is given in *table 14*, and the gauge length dependant elongation in jointed aramid yarn can be broken down into two discrete components, true material creep in the yarn and some slippage or tightening of the mechanical joint. *Figure 48* shows elongation in jointed aramid yarn resolved into the two components for a 400 mm gauge length with single 40 mm joint. The figure resolves the creep in unjointed yarn and creep in jointed yarn into components by showing that by subtracting creep in unjointed yarn from creep in jointed yarn the movement of the joint is obtained.

The gauge length dependence of creep in jointed aramid yarn is shown in *figure 49*. The 100% Y-axis datum represents the level at which the creep rate of jointed and unjointed yarn materials are the same. Gauge lengths in excess of 10 m result in the creep performance of jointed yarn being very close to that of unjointed yarn containing one 40 mm splice. The ratio of unjointed to jointed material is the splice ratio as shown in *figure 50*. The splice ratio is a useful parameter which allows the comparison of data from yarn tests which may contain more than one joint or a joint of different dimensions to the joints presented in this thesis.

Figure 51 is a plot of average LASE data for jointed and unjointed yarn, the data was produced by the material yarn LASE test method, using a 40 mm gauge length and 40 mm long joints. The jointed data therefore refers to joint LASE performance only. The joints which have an effective linear density of 2 x 1580 (= 3160 dtex) pull together under tension resulting in apparent "strain hardening" behaviour and tensile performance better than unjointed material above 0.4% strain on the first tensile loading (first pull). Plotting **Elongation of Jointed Yarn as a % of Unjointed Yarn** against **Gauge Length of Yarn with Single 40 mm Joint (m)** as in *figure 52* gives a comparison of the LASE performance of jointed yarn with the LASE performance of unjointed yarn. The plot shows that above 3 m gauge length with one 40 mm joint the LASE performance of jointed yarn is very close to the LASE performance of unjointed yarn. As before *figure 53* shows the LASE performance results in terms of the splice ratio parameter.

4.5 Ageing and Weathering Test Results

Ageing test results consist of tensile, LASE and fatigue test results produced by the test methods described. Material yarn tensile test results for Twaron, Kevlar and Dyneema material yarns are given. Students t-test results for testing results are also given where hypothesis **H0** and hypothesis **H1** are :

> **H0 : The average tensile breaking load (strength) of the unaged samples is the <u>SAME</u> as the average tensile breaking load (strength) of the aged samples.**

And :

H1 : The average tensile breaking load (strength) of the unaged samples is <u>NOT THE SAME</u> as the average tensile breaking load (strength) of the aged samples.

4.5.1 Ageing and Weathering Tensile Test Results

4.5.1.1 Hydrochloric Acid Ageing Test Results

Test results for acid aged material yarns are given in *tables 15, 16 & 17*, and *figures 54 & 55*. Results tables give the tensile test results and t-test results, the *figures 54 & 55* show plots of **Breaking Load** against **Duration of Ageing**. Results for Twaron and Kevlar show that ageing in 1 molar hydrochloric acid resulted in a reduction in the average tensile strength of the yarns, this reduction was due to the ageing effects of acid and heat. *Figure 54* shows that the strength reducing effects increase with increased temperature. Observed loss of tensile strength decreases non linearly with increased testing temperature where the effect of temperature increase on tensile strength is greatest at higher temperatures. The tensile strength of Dyneema fell initially due to the effects of ageing but then did not show an observed progressive loss of strength with time and elevated temperature.

Figure 55 shows the effect of chemical concentration on tensile strength. Increased chemical concentration can be seen to result in an increased reduction in tensile strength. The tensile strength of the aramid materials progressively deteriorated with time.

4.5.1.2 Sodium Hydroxide Ageing Test Results

The performance of the two aramid materials as shown by the alkali ageing test results given in *tables 18, 19 & 20* and *figure 56* are very similar. Alkali aged aramid materials show the same ageing behaviour as acid aged aramid materials. Behaviour is characterised by progressive loss of tensile strength with time due to the effects of ageing. Dyneema also shows the same material performance characteristics in alkali and acid solutions. The tensile strength of alkali aged Dyneema is also reduced by the effects of time and temperature but to a lesser extent than the aramid materials.

4.5.1.3 Detergent Ageing Test Results

The results for material aged in 1% Antarox CO-630 detergent solution at 23°C and 80°C are shown in *tables 21, 22 & 23*, and *figure 57*. Ageing did not reduce the tensile strength of aramid yarn at test durations of less than 500 hours. Above 500 hours only small strength losses due to detergent ageing are recorded. At 80°C a progressive loss of tensile strength is recorded, with Kevlar results showing a greater loss of strength than Twaron. No significant tensile strength reduction of Dyneema was recorded.

4.5.1.4 DERV Diesel Oil Ageing

DERV diesel oil ageing tensile test results as given in *tables 24, 25 & 26*, and shown graphically in *figure 58*. The results indicate that Twaron, Kevlar and Dyneema within the scope of the testing did not suffer a significant reduction in tensile strength due to ageing effects.

4.5.1.5 Petrol Ageing Test Results

The petrol ageing test results shown in *tables 27, 28 & 29* and *figure 59* show that for the two aramid materials an initial small reduction in tensile strength is not accompanied by any further strength reduction up to the end of the period of testing. The same ageing behaviour is also true of Dyneema.

4.5.1.6 Tap Water Ageing Test Results

Tap water ageing test results are given in *tables 30, 31 & 32* and *figure 60*. From results for aramid aged at 23°C it is unclear whether tensile strength reduction took place or not. At 80°C strength reduction due to the effect of heated water was recorded after 500 hours duration. The results for Dyneema show a small reduction in tensile strength at the test start and then no further strength loss.

4.5.1.7 Thermal Ageing Test Results

Results for thermally aged material yarns are given in *tables 33, 34 & 35* and *figure 61*. The aramid results indicate a progressive loss of tensile strength due to the ageing effect of heat. The strength losses recorded are greater for Kevlar than for Twaron, an average difference of 24.3 N was recorded after ageing at 150°C for 1000 hours. The results for Dyneema indicate severe loss of tensile strength at the specified temperatures. For the three materials a lower tensile strength is recorded after ageing at the highest temperature than the lowest temperature.

4.5.1.8 Ultra Violet Ageing Test Results

The u.v. ageing test results shown in *tables 36, 37 & 38* and *figure 62*. The aramid results show a progressive loss of tensile strength due to ageing for all materials. Kevlar performed better than Twaron, where an average difference of 18.4 N was recorded after 1000 hours of u.v. ageing. Dyneema results show a severe progressive loss of tensile strength with all samples failing completely before the projected test end. Failed samples of Dyneema were extremely brittle and could be pulled apart in the hand. Manufacturers claim good u.v. resistance in common with many other polyethylene materials, so this result was not predicted.

4.5.1.9 Saturated Salt Water Ageing Test Results

Saturated salt water ageing test results are shown in *tables 39, 40 & 41* and *figure 63*. The results for Dyneema and the aramid materials show the ageing not to have reduced the strength of the materials at 23°C. The ageing process resulted in a slight progressive strength reduction at 80°C. The performance of the two aramid materials in the tests showed characteristic similarity.

4.5.2 Ageing and Weathering LASE Test Results

LASE test results for aged Twaron, Kevlar and Dyneema are compared with LASE test results for unaged Twaron, Kevlar and Dyneema to assess whether ageing gives rise to material softening or hardening which will affect finished cable tensile performance (t-test not applied due to small sample size). LASE test results for unaged yarns are given in *table 42* and summarised in *figures 64 & 65*. Results for Kevlar aged at 0.5% strain on the environmental weathering frame are also given.

4.5.2.1 Acid Ageing LASE Test Results

The results given in *table 43* show the effects 1m hydrochloric acid on Kevlar result in a reduction in Young's modulus (softening or loss of rigidity). The results for Kevlar also show a reduction in LASE performance at 0.5% strain by 4 N, the results for Twaron show a reduction in breaking strain from 2% to below 1% The results however do not show that the LASE performance of Twaron was reduced. The results for Dyneema indicate a 6% reduction in Young's modulus and 12 N reduction in LASE performance at 0.5% strain due to the effects of acid ageing.

4.5.2.2 Alkali Ageing LASE Test Results

The results given in *table 44* for aramid and Dyneema aged in 1m sodium hydroxide indicate a reduction in Young's modulus and LASE at 0.5% strain performance due to prolonged exposure to the ageing medium. The Young's modulus reduction was 9.9%, and the LASE reduction at 0.5% strain was 6 N for Twaron. The Young's modulus and LASE at 0.5% strain reduction were 5 N and 8.2% for Kevlar and 4 N and 3.8% for Dyneema. A similarity in ageing behaviour of materials aged in the acid and alkali solutions is apparent, a common link between acid and alkali ageing is explored in the discussion.

4.5.2.3 Detergent Ageing LASE Test Results

Detergent ageing LASE test results are given in *table 45*, the results for Twaron indicate that the 1% antarox detergent solution did not reduce the performance of the material. The results for Kevlar show an unaltered modulus value with a reduced load at 0.5% strain by 5 N. Dyneema results show reduced modulus and LASE values due to detergent ageing, the Young's modulus was reduced by 11.8% and the LASE at 0.5% strain by 12 N.

4.5.2.4 Diesel Ageing LASE Test Results

The results given in *table 46* show that for Twaron no change in LASE at 0.5% or Young's modulus resulted from diesel ageing. The LASE at 0.5% for Kevlar was reduced by 3 N and the Young's modulus was reduced by 3.3% The LASE at 0.5% for Dyneema was reduced by 2 N and the Young's modulus was reduced by 1.3% Diesel ageing results indicate small or no change in measured material properties resulted from ageing.

4.5.2.5 Petrol Ageing LASE Test Results

The results given in *table 47* show that for Kevlar no change in LASE at 0.5% or Young's modulus resulted from diesel ageing. The LASE at 0.5% for Twaron was reduced by 4 N, the Young's modulus remained unaltered. The LASE at 0.5% for Dyneema was reduced by 10 N and the Young's modulus was reduced by

13.6% Petrol ageing results indicate that for aramid materials small or no change in measured material properties resulted from ageing, a common link with diesel aged aramid is therefore possible due to the mineral oil nature of petrol and diesel. Dyneema results indicate clear reduction in material performance due to ageing in petrol.

4.5.2.6 Tap Water Ageing LASE Test Results

The aramid tap water ageing LASE test results are given in *table 49*. The tap water results for aramid materials like the results for diesel and petrol indicate no change in tensile performance due to the effects of ageing. Dyneema results indicate an increase in modulus and LASE performance as a result of tap water ageing. As stated previously in this thesis for aramid the water ageing results presented in this thesis were expected as the last stage in aramid production is a multiple stage washing process to remove solvents. The increase 7.4% increase in Young's modulus for Dyneema was due to the way that wetting reduced the materials tendency to fluff and the material remained tightly bundled together when re-dried.

4.5.2.7 Thermal Ageing LASE Test Results

Thermal ageing LASE test results are given in *table 49*. The results for aramid materials indicate that there was no change in LASE at 0.5% strain, there was a

2.2% reduction in Twaron Young's modulus, and a 5.6% reduction in Kevlar Young's modulus due to ageing. Dyneema results show a clear reduction in LASE and modulus due to the effects of thermal ageing, Young's modulus was reduced by 22.7% and LASE at 0.5% strain by 16 N.

Standard cable maximum operating temperature is 80°C and the extrusion of an oversheath takes place at no more than 190°C. Aramid materials are able to withstand oversheathing and service conditions but Dyneema would not be able to withstand the oversheathing process but could withstand normal operating conditions. The application of thermal barrier tapes over Dyneema is possible but not a viable option due to cost and cable weight considerations.

4.5.2.8 Ultra Violet Ageing LASE Test Results

Ultra violet ageing LASE test results are given in *table 50*. The results for aramid materials indicate that a 1 N reduction in Twaron LASE at 0.5% strain occurred and a 4.5% reduction in Kevlar Young's Modulus. In common with other aged material LASE and Young's modulus results given in this thesis the sample size of three makes assessment of levels of significance unrealistic. The small changes in LASE and Young' modulus cannot therefore be taken as absolute proof of changes due to the effects of ageing. No LASE and Young's modulus results are given for Dyneema due to complete failure of samples before the 1000 h end of test.

4.5.2.9 Saturated Salt Water Ageing LASE Test Results

Saturated salt water ageing LASE test results are given in *table 51*. The results for aramid show a reduction in load at 0.5% strain of 2 N for Twaron and 5 N for Kevlar without a change in modulus. The results suggest a modified or non linear LASE performance. Dyneema results indicate a reduction in LASE and modulus of 16 N and 13.5% respectively. It is apparent that within the limits of the testing carried out that exposure to salt water resulted in no deterioration of aramid material LASE at 0.5% strain and Young's modulus properties whilst those of Dyneema did deteriorate.

4.5.3 Aged Yarn Fatigue Test Results

Comparison is made here between yarn samples that have been aged, subjected to 10,000 fatigue cycles at an initial 0.5% strain then tensile tested to failure with (**A**) unaged yarn that has been tensile tested only. A second comparison is made between yarn samples that have been aged, subjected to 10,000 fatigue cycles at an initial 0.5% strain then tensile tested to failure with, with (**B**) unaged yarn that has been subjected to 10,000 fatigue cycles at an initial 0.5% strain then tensile tested to failure. Test "A" gives the tensile strength reduction due to the combined effects of ageing and fatigue cycling and test "B" gives the tensile strength reduction due to ageing alone. Subtracting the tensile strength reducing effects of test "B" from test "A" gives the strength reducing effects of fatigue cycling alone. Unaged yarn fatigue test results are given in *table 52*, and fatigue test results are shown graphically in *figures 66, 67 & 68*.

4.5.3.1 Acid Ageing Fatigue Test Results

The results for acid aged Twaron, Kevlar and Dyneema are shown in *table 53*. The Twaron results show that the tensile strength of the material decreased as a result of the combined effects of ageing and fatigue cycling. A 51% strength reduction is attributable to ageing and 2% to fatigue cycling. The strength of Kevlar also was reduced as a result of a combination of ageing and fatigue cycling, 2% was due to fatigue cycling and 62% due to ageing. Strength loss due the combined effects of ageing and fatigue cycling is also recorded for Dyneema. The strength of Dyneema after testing is significantly higher than the strength of the aramid materials where a 19% reduction is attributable to ageing and 13% to fatigue cycling.

4.5.3.2 Alkali Ageing Fatigue Test Results

Results are given in *table 54* for the aramid materials which record a loss of tensile strength due to the effects of ageing and fatigue cycling. For Twaron 46% was due to ageing and 3% was due to the effects of fatigue cycling. For Kevlar 40% was due to ageing and 3% was due to the effects of fatigue cycling. Dyneema results show a 14% decrease of tensile strength due to ageing only.

4.5.3.3 Detergent Ageing Fatigue Test Results

Detergent aged fatigue test results are shown in *table 55*. The results for Twaron and Kevlar show an 20% loss of strength due to the combined effects of ageing and fatigue cycling, of that 20%, 17% is due to ageing and 3% is due to the effects of fatigue cycling. The Dyneema results show an approximate 20% strength loss due to the combined effects of ageing and fatigue cycling with 10% attributable to ageing and 10% attributable to fatigue cycling.

4.5.3.4 Diesel Ageing Fatigue Test Results

The DERV diesel oil ageing results are shown in *table 56*. The results for Twaron indicate an 11% tensile strength loss due to ageing and a 5% tensile strength loss due to fatigue cycling. Kevlar results indicate an 18% strength loss due to ageing and a 3% strength loss due to fatigue cycling. Dyneema results indicate an approximate 4% strength loss due to ageing and a 3% strength loss due to fatigue cycling.

4.5.3.5 Petrol Ageing Fatigue Test Results

Petrol ageing results are similar to diesel ageing results and are given in *table 57*. The results for Twaron indicate a 17% strength loss due to ageing and a 5% strength loss due to fatigue cycling. Kevlar results indicate a 10% strength loss due to ageing and a 4% strength loss due to fatigue cycling. Dyneema results record an 8% strength loss due to ageing and a 12% strength loss due to fatigue cycling.

4.5.3.6 Tap Water Ageing Fatigue Test Results

Tap water ageing fatigue test results are given in *table 58*. Twaron results show an 4% tensile strength loss due to fatigue cycling and a 20% strength loss due to ageing. Kevlar results show an 4% tensile strength loss due to fatigue cycling and a 12% strength loss due to ageing. Dyneema results show an approximate 15% tensile strength loss due to fatigue cycling and a 9% strength loss due to ageing. A pattern of results has emerged where the two aramid materials again exhibit a similar to each other. Dyneema results show the strength reducing effect of fatigue cycling to be less than those of the aramid materials, this result is due to the inherent smoothness of UHMWPE yarn. Aramid tends to become rougher with ageing due to decomposition of spin finish.

4.5.3.7 Thermal Ageing Fatigue Test Results

Thermal ageing fatigue test results are given in *table 59*. The Twaron results show a 3% strength loss due to fatigue cycling and a 47% strength loss due to ageing. The Kevlar results show a 1% strength loss due to fatigue cycling and a 68% strength loss due to ageing. The Dyneema results show a 10% approximate strength loss due to fatigue cycling and a 29% strength loss due to ageing. The results for aramid are surprising since thermal ageing removed the smooth spin finish leaving a rougher yarn more susceptible to abrasion yet very low strength reductions due to abrasion are recorded.

4.5.3.8 Ultra Violet Ageing Fatigue Test Results

Results for ultra violet aged fatigue tested Twaron, Kevlar and Dyneema are given in *table 60*. Twaron results indicate 3% loss of strength due to the effects of fatigue cycling plus 40% loss of strength due to ultra violet ageing. Kevlar results indicate 3% loss of strength due to the effects of fatigue cycling plus 37% loss of strength due to ultra violet ageing. Dyneema results are not given due to complete failure of the test samples.

4.5.3.9 Saturated Salt Water Ageing Fatigue Test Results

Table 61 gives the saturated sodium chloride solution ageing fatigue test results. Twaron results indicate 4% loss of strength due to the effects of fatigue cycling plus a 22% loss of strength due to SSW ageing. Kevlar results show a 3% loss of strength due to the effects of fatigue cycling plus a 19% loss of strength due to SSW ageing. Dyneema results show a 12% loss of strength due to the effects of fatigue cycling plus 13% loss of strength due to SSW ageing.

4.5.4 Outdoor Weathering Test Results

Outdoor weathering test results are given in *table 62*, and are shown in histogram form in *figure 69*. Results show that one sample from the original ten samples failed prematurely at the top termination and is not considered further. The remaining nine samples failed between 292 and 375 days of testing at an initial 0.5% strain, where average test duration was 337 days. All samples failed by visible mechanical abrasion at the central contact point due to wind buffeting of loaded samples. Discolouration and contamination by environmental contamination was evident. Weathered yarn had discoloured from a yellow to dull brown. Outdoor weathering test results indicate the key role of mechanical abrasion in tensile strength reduction of aramid yarn. It is therefore likely that based on the results of fatigue and outdoor weathering tests abrasion is the key strength reducing mechanism in aerial cables subject to aeolian vibration.

5.0 DISCUSSION

5.1 Yarn Tensile Behaviour

The tensile performance of equivalent grades of Twaron and Kevlar are very similar *(figure 30)*, although this study has not taken into account variation in properties from one bobbin to another, or from different production batches. Aramid tensile test results and observations have shown that tensile performance is a product of true material strength and fibre orientation. Attempt were made in the course of testing to smooth the yarn when handling it to maintain fibre orientation. Tensile strength is greatest where all fibres are neatly aligned parallel to each other and under the same tension. In practice a range of fibre paths (fibre routings through the bundle) and tensions exists such that fibres under the greatest tension break first initiating a cascade of fibre failures. A wide range of paths and tensions leads to fluffy or tangled yarn. The annealing process that occurs during manufacturing breaks a small number of the 1000 fibres in a 1580/1610 dtex yarn end so that some damage is likely in virgin yarn. Twisting yarn can improve tensile performance by reducing tension differences and path difference variation whilst allowing broken fibres to contribute to the overall tensile strength of the yarn, this due to frictional gripping and entanglement.

Impurities in aramid are concentrated at fibre centres, hoop stresses induced into the yarn by the densification and contraction process during manufacture and microvoids act as sites for the initiation of yarn failure [22]. Aramid that has been subjected to compression and UHMWPE generally fail in tension at kink band sites (fibre imperfections) [26]. The distribution of failure sites and voids, density and fibre diameter variations control the tensile failure behaviour of individual fibres [10,11,12].

The observed longitudinal splitting of aramid yarn and to a lesser extent UHMWPE is due to breaking of the weak lateral bonds between molecules [26] to give a typical "tomato centre" (longitudinally split and curled) profile to tensile tested yarn. The ranked tensile test distribution results for aramid *(figure 26)*, show the strongest and weakest 20% of the results to be stronger and weaker respectively than would be predicted by the regression of the ranked data. UHMWPE tensile test data also shows a degree of non linearity where differences in breaking load are due to a difference in failure site distribution where a close spacing of flaws results in a reduced tensile breaking load [22], and or variation in fibre orientation due to handling and rewinding.

The tensile distributions of the aramid materials are very close to true Gaussian distributions and are therefore suitable for Weibull treatment *(figure 30)*. The tensile distribution of UHMWPE is skewed towards the higher tensile strength groupings *(figure 29)*. This distortion is believed to be due to the electrostatically charged nature of dry UHMWPE giving rise to fluffing and fibre disorder reducing the number of mid strength tensile results. The tensile breaking load of UHMWPE can be increased by wetting the yarn to achieve improved fibre orientation and eliminate electrostatic charging. Aramid materials do not suffer the effects of electrostatic charging and fluffing due to the application of a vegetable oil spin finish coating.

The Weibull shape parameters $\mathbf{m_w}$ produced from project tensile test data *(figures 31, 32, 33 & 34)* are significantly higher than published values indicating a greater range of test results [19,20]. The difference is believed to be due to test differences and aramid configuration. The project tensile test used 1000 fibre aramid yarns wrapped around metal capstans *(figure 4)*. Workers in the past have concentrated on tests using single fibres glued onto tabs.

5.2 Yarn LASE Behaviour

The LASE behaviour of the strength member yarn exhibits an increasing modulus, where the Young's moduli increase with increased tensile strain *(figure 35)*. In every case pretension was required to reduce the spread of results by improving fibre alignment and reducing tension differences and path differences between fibres. The yarns were characterised by repeatable LASE results without deterioration in LASE performance below breaking strains. The test method was successful in eliminating test end effects and strain gauge slippage.

The LASE performance of Twaron and Kevlar were once again very similar within the constraints of material selection and testing. The performance of the aramid materials was superior to the other materials in terms of the tenacity (strength per unit weight parameter) *(figure 36)*. The use of E-glass yarn would lead to increased cable weight and the use of UHMWPE would lead to increased bulk (cable diameter) when compared with aramid materials. Cable weight and cable diameter minimisation are of supreme importance in ADSS (All Dielectric Self Supporting) aerial cable designs. Minimum cable diameters are required to reduce wind and ice loadings. Reduced cable weight allows the use of longer spans or reduced cable tension.

Cable composite moduli are dependant on the ratio of contribution of GRP central strength member to peripheral stranded strength members *(figure 37)*. The strength contribution of two separate types of strength member results in a cable product with a composite LASE performance which is both gauge length dependant, and dependant on the installation or tensile testing technique used. The LASE contribution of the central GRP rod is close to linear (constant Young's modulus) with an origin at zero load and strain. Aramid peripheral strength members will lose stranding back tension from both ends axially inwards towards the cable centre particularly where no hot melt adhesive or other low shear compounds are used. The application of sheaths such as low or medium density polyethylene compounds increases this effect due to a residual axial stress upon cooling and contraction after sheathing.

The net effect is that an initial strain is required to pull the aramid taught and straighten out any crinkling up of the aramid that may have occurred. This effect from work carried out by Pirelli Cables is known to be gauge length dependant, the effect tending to be less noticeable in longer lengths due to the confining and frictional effects of the sheath and core. The effect was observed in the tests carried out as part of this study where a cable strain of 0.6% was required to achieve aramid strength contribution. At cable strains in excess of 1% the strength contribution was 80% aramid, and 20% from the GRP central strength member. The cable data given here is first pull data, upon successive pulls the bedding in (initial aramid strain) effect becomes less and less marked as the aramid tension lost after stranding is restored by applied tension. The value of load taken as the creep load was the true load required to achieve a cabled aramid strain of 0.5%

5.3 Yarn Creep Behaviour

The creep rate of a material is defined as the slope of its graph of creep strain against time, and is given by $\mathbf{d\epsilon/dt}$, where ϵ is the strain due to creep and $\mathbf{t}$ is the duration of the creep process. Such creep curves are frequently divided into various stages. Following the application of the load, the creep rate, initially at its maximum, decreases during "primary" or "transient" creep to a constant, minimum value known as "secondary" or "steady state" creep. At a later stage, known as "tertiary creep" the creep rate may again accelerate prior to fracture. In materials showing this form of creep behaviour, the constant steady state or secondary creep rate is often used to characterise the stress and temperature dependence of the process.

For creep in aramids a different form of time dependence has been reported [14], in which a plot of creep strain against log time (seconds) produces a linear relationship. The slope of the line **dϵ/dlogt**, is expressed as creep strain per decade of time, and is referred to as the log creep rate. Although this log creep rate appears to be constant in reality it represents a true creep rate which decreases continuously with time. Thus a true secondary or steady state creep rate is not achieved in this case.

Comparing the log and linear creep plots for aramid and glass materials the rate results show a similar flattened profile and therefore do not conclusively depict the log nature of creep in these materials *(figures 38 & 39)*. However standard deviations of the first creep data points for each material were high *(tables 10, 11 & 12)*. The standard deviations of later data points were greatly reduced as practice with the measurement method were gained. Work by aramid manufacturers and other workers has proved the logarithmic nature of creep which on a linear plot can be seen to slow down with time [3,31]. Twaron and Kevlar behaviour in the yarn creep tests, and from manufacturers data was very similar [3,7]. The log creep rates of the aramid materials were shown to be linear up to or beyond eight months of testing *(figure 41)* [30], this finding is not surprising as aramid log creep rates are known to be linear beyond five years. Creep in aramid is claimed to be wholly recoverable [23], however creep recoverability was not tested as part of this study.

It has been shown that aramid creep data follow the Arrhenius relationship [31] for the effects of temperature and mechanical stress [31], although further work at different temperatures would be required before a value for creep activation energy could be determined. The aramid log creep results produced as part of this project were appreciably higher than those published by other workers and aramid manufacturers *(table 11)*. Log creep rates in Twaron and Kevlar were found to be 0.033 %/dec in this study [30], manufacturers quote less than 0.020 %/dec [3,31]. Creep and photodegradation in aramid are strongly believed to be due to molecular chain scission by breakage of carbon-nitrogen bonds. The creep test specimens were stored uncovered in daylight near south facing windows [23], it is possible that the high material yarn creep rates presented in this thesis are due to a combination of true mechanical creep and photodegradation (ultra violet degradation), this situation was not anticipated as aramid suppliers carry out eight day creep tests in daylight, no light monitoring was performed. It is therefore difficult to understand how the effects of creep and degradation are wholly or even partially reversible !

The creep results for Dyneema *(figure 41)* show log creep rates which are appreciably higher than those of the other materials and which increase (accelerate) with log time [30]. The behaviour is clearly different, and may be attributable to molecular chain slippage of the orientated UHMWPE molecule [26]. The material on the basis of creep performance is unsuitable for ADSS aerial cable non metallic strength member applications due to the inability of the strength member to restrict cable strain and consequential optical fibre strain with system attenuation. E-glass yarn data showed the lowest linear log creep rate of all the materials tested at 0.011 %/dec *(table 11)*. The figure is also believed to be typical of GRP rods which essentially contain the same type of glass bonded in a polyester resin matrix although no direct evidence has been found. The log creep results were linear providing that the yarn was not kinked causing fibre breakage and failure upon application of the creep loading.

5.4 Cable Creep Behaviour

Cable log creep results show a short initial phase of primary creep which is less than that predicted by the log dependence *(figure 43)*. After the initial phase the creep follows the log time dependence. The cable log creep rate was the same as the manufacturers data for Twaron yarn at 0.016 %/dec *(table 12)*. The result can be explained by observing that no adverse processes giving rise to additional yarn strain occurred [30]. Such hypothetical processes may include a straightening out of cable aramid lay or increased core grip under load [30]. It is **not** possible that the GRP central strength member contributed to the overall low creep rate of the cable since it was removed from the cable prior to testing.

No cable twisting due to torque imbalance was observed indicating even dextral (left hand stranding rotation), and sinistral stranding (right hand stranding rotation), and a core/peripheral armouring torque balance. The results shown here point to a creep related strain of 0.15% after 40 years under a loading giving an initial 0.5% strain *(table 12)*. This value must be considered more of a minimum than an absolutely reliable guide. The result does offer a degree of reassurance for a predicted product lifetime of 40 years.

5.5 Yarn Fatigue Behaviour

Once again Twaron and Kevlar are characterised by a striking similarity in material performance *(table 13 & figure 46)*. The reason is in part due to the very similar nature of the friction reducing spin finish applied to the aramid fibres. All materials to differing degrees suffered from the effects of mechanical abrasion at clamps and around capstans (stress concentrators). E-glass yarn suffered most from the effects of mechanical abrasion failing completely during the test [30], *(figure 47)*. A general pattern to the material strength loss emerged where after the onset of fibre breakage rapid fluffing, further fibre breakage and rapid strength loss took place. The role of the cable designer in this situation is to defer the onset of abrasion by the application of friction reducing substances and limiting points of stress concentration.

The study has shown aramid to be a good all round communication cable peripheral strength member material. In aerial applications the aramid should be impregnated with hot melt adhesive to bond the fibres rigidly in place, or lubricated with a substance such as PIB to reduce fibre contact and friction. The difference in the two approaches lies in the requirement for sheath grip. High shear force hot melt adhesives bond the sheath to the aramid strength members allowing installation by sheath grip techniques such as reusable pulling stockings.

PIB materials have a lower shear strength with lubricating properties and are ideally suited to installation techniques which may include blowing by water or air, and pulling eyes attached to the central and peripheral strength members. Owens Corning E-glass yarn is supplied with a soft polyurethane coating but still suffers greatly from the effects of bending and abrasion due to fatigue cycling. E-glass of this type is not recommended for ADSS aerial applications on the basis of poor fatigue performance. E-glass is however suitable for duct type applications where strength is only required during manufacture and installation.

Dyneema performed well under cyclic loading, suffering less in the way of strength reducing effects through abrasion than the other materials due to its inherently smooth surface finish *(figure 47)*. Unfortunately poor creep performance and greater bulk (increased cable bulk leads to increased cable diameters) make Dyneema unsuitable for ADSS aerial cable applications *(figure 40)*.

5.6 Jointed Yarn Behaviour

The virtually linear LASE performance of the unjointed yarn is the key design criterion for the tensile performance of optical cables *(figure 51)*. Joints have been shown to offer superior LASE performance particularly at high tensile loadings and resultant strains in excess of 0.5% It is therefore **NOT** necessary to make any modification or amendments to existing design procedures as results point to an improved rather than a worsened LASE performance due to jointing.

Tensile test data for jointed aramid is gauge length dependant, where the gauge length dependence is due to the way total yarn strain is comprised of two separable discrete components. The two components are splice strain and the strain in the rest of the unjointed yarn. Each joint was 40 mm in length and so the LASE performance of a splice is consistent irrespective of the length of unjointed yarn to which the splice is attached. The remainder of the unjointed yarn is variable in length and so therefore is the resultant strain *(figure 52 and 53)*.

The significance of this finding is that the longer the length of unjointed yarn containing a single joint, the closer the LASE performance approximates to unjointed yarn as the measured effect of the splice diminishes. The net effect of adding one 40 mm joint is that the tensile performance of a 3 m length of jointed yarn at 0.5% strain is virtually the same as a 3 m length of unjointed yarn. The implications of this and all other LASE results up to the aramid breaking strain of 2% is that a typical 2 Km length of cable could potentially contain a large number of joints in all aramid ends without deterioration in cable tensile performance. The splice ratio parameter allows for the possibility of performance calculations where more than one joint is used in any length of yarn. The effect of hot melt adhesive applied to joints in cables would be likely to reduce the effect of joints further, but this would require further investigation.

The linear density of the joint is twice that of the virgin yarn but slippage and tightening of the joint on the first pull gives rise to a higher local strain at the joint upon loading. Slippage of the fibres that constitute the joint dominates up to a tensile strain of 0.4% At strains between 0.4% and 2.0% the LASE performance of the joint is superior to that of virgin yarn due to the greater amount of strength contributing material at that point. Cable creep performance of jointed yarn is also gauge length dependant. The creep test gauge length dependence obeys the same rules as the LASE test gauge length dependence for precisely the same reasons. In the case of creep a length of 5 m of yarn containing one joint is sufficient for the creep performance to be virtually indistinguishable from that of unjointed material. However the shorter 400 mm creep test samples appeared to suggest that the log creep rate of jointed Kevlar was higher than that of unjointed material as the gauge length of the jointed material was less than 5 m and within the gauge length dependency range *(figure 41 & table 11)*.

The fatigue test performance of jointed aramid was comparable with that of OFY 680 glass yarn, but was not as good as unjointed aramid *(figure 47)*. A slow progressive pulling apart of the joint occurred after 100,000 fatigue cycles. 40 mm Joints in 1580/1610/3160/3220 dtex aramid are therefore not recommended for use in aerial applications, but are highly recommended for use in duct, direct buried and internal type applications without restriction.

The tensile strength of fatigue tested jointed aramid yarn was observed to increase slightly due to fatigue cycling before the effects of mechanical abrasion caused tensile strength reduction *(figure 46)*. This phenomenon occurs as result of improved load sharing of the individual fibres that make up the yarn. The cycling effectively massages the fibres which are able to move within the yarn bundle, so that they adopt a narrower range of tensions and path differences leading to a more even fibre load sharing. An initial slippage of tangled yarn occurred before a more permanent arrangement occurred, as in the tensile testing. The undesirable abrasion effects at capstans and clamps were observed to be the same for jointed and virgin yarn.

5.7 Ageing and Weathering Behaviour

Aramid is characterised by the presence of benzene rings which give thermal stability up to 450°C, the thermal stability of aramid results in suitability for cable making processes such as sheathing at 180°C *(figure 2)*. UHMWPE does not posses such thermal stability as was evident from the thermal ageing test results, and could not be processed using current cable making processes. Aramid however is recognised as possessing poor alkali resistance a finding supported by the work presented in this thesis [23] *(figure 61)*. The ageing mechanism in aramid materials like the creep mechanism is believed to be molecular chain scission [26]. The ageing mechanism in UHMWPE is not clear, the molecular chain slippage mechanism identified for creep does not explain loss of tensile strength due to exposure to ageing solutions. Where no ageing data is given, for example Dyneema aged by u.v. radiation and condensation cycles for 1000 hours, the sample failed completely and was too frail to be unwound from the ageing bobbin *(table 38)*.

Exposure of aramid to acid and alkali solutions resulted in some cases in total loss of strength and was an indication of the susceptibility of aramid to the strength reducing effects of certain ionic polar molecules but not saline solutions *(figure 54, 55 & 63)*. Dyneema was less sensitive to the effects of polar molecules than aramid. Aramid possesses very little ageing susceptibility to saline solutions and mineral oils *(figure 58, 59 & 63)*, a finding which is of importance for certain industrial designs, and cables used in coastal applications. Twaron, Kevlar and Dyneema are all insensitive to tap water *(figure 60)*, this result is not a surprise since the last stage in the production of aramid is multiple washing and drying to remove solvents.

Aramid yarn was adversely affected by the effects of ultra violet radiation, but not to the same degree as Dyneema *(figure 62)*. Polyethylenes used in other applications such as cable sheathing are made black by the addition of carbon or loaded with several percent by weight of antioxidants and ultra violet stabiliser. The naturally white UHMWPE does not enjoy such protection and consequently failed completely in the ultra violet radiation ageing tests *(figure 62)*.

Ageing effects generally were shown to increase in a non linear fashion with increased temperature and concentration as shown by the acid ageing results *(figures 54 & 55)*. The project results point to a need to protect aramid stranded cables from the prolonged adverse effects of ageing by the continued use of water blocking substances and oversheaths. The issue of molecular permeation through cable sheath may however influence results but is not considered here.

Aramid LASE performance changed little due to the effects of ageing *(figures 64 & 65)*, an important finding since cable tensile performance is based on LASE data. The fatigue performance of aramid deteriorated as a result of ageing before fatigue cycling where the reduction in tensile strength in all cases was greater than for fatigue tested yarn alone *(figures 67 & 68)*. The deterioration in fatigue performance due to ageing was observed to be attributable to fibre surface roughening through spin finish removal due to ageing, leading to increased fibre breakage due to mechanical abrasion. Dyneema was more susceptible than aramid to LASE reduction due to ageing but was less susceptible to strength loss due to ageing and fatigue cycling. Dyneema suffered less of a deterioration in strength due to ageing and fatigue cycling resulting from the naturally smooth fibre surfaces not requiring spin finish.

Outdoor weathering test samples failed through the effects of mechanical abrasion *(table 62 & figure 69)*. Although typically discoloured to a coffee brown colour due to the effects of u.v. radiation [3], the environmental tests under strain indicated a huge acceleration factor in the ageing tests and must therefore be a source of reassurance.

6.0 CONCLUSIONS

1) Twaron and Kevlar test results are characterised by a very close similarity in material performance.

2) In terms of yarn and cable tensile performance, aramid materials offer mechanical benefits over E-glass and UHMWPE materials. Cost benefits also apply but are not considered here.

3) The observed composite Young's modulus of the cable samples is due to the gauge length dependant phenomena of aramid "bedding in".

4) Manufacturers and other independent sources have found the log creep rates of Twaron and Kevlar to be virtually the same, this study being no exception. This study recorded log creep rates for Twaron and Kevlar that were higher than those recorded by other workers despite developing a method free from stress concentrating end effects. This result is believed to be due to ultra violet degradation.

5) The log creep rate of Owens Corning OFY 680 was the lowest of the materials tested, and is believed to be typical of the type of GRP rod used for cable central strength members. The GRP rods use the same type of borosilicate E-glass fibres as strength members.

6) Cable creep results after an initial fluctuation where the creep rate is less than that predicted by the log dependence increase to meet the log dependence. The log creep rate is then close to that of the accepted manufacturers values for aramid of 0.017 %/dec (0.016 %/dec for Twaron and 0.0185 %/dec for Kevlar).

7) The work has identified mechanical abrasion as a possible source of strength loss of aramid in aerial cable applications which are held at clamps (stress concentrators), and subject to vibration such as rapid aeolian vibration typically 50-100 Hz, or high amplitude low frequency galloping.

8) The work has identified a continued need to impregnate aramid to either lubricate or restrict aramid fibre-fibre and aramid fibre-cable movement to reduce abrasion.

9) Owens Corning OFY 680 suffered particularly badly from the effects of mechanical abrasion due to fatigue cycling. Fibre-fibre, clamp and capstan abrasion were observed.

10) Jointed aramid has been shown to have gauge length dependant creep and LASE properties. The effects are such that jointed yarn can be used in communication cable applications without adversely affecting cable tensile or creep performance.

11) Joints are viewed as an acceptable means of reducing aramid scrap levels where short lengths can be jointed together and used in duct, direct buried and internal communication cable applications.

12) The fatigue performance of 40 mm joints of the type used on 1580/1610 dtex and 3160/3220 dtex aramid has revealed a susceptibility to pulling apart of the splice with prolonged fatigue cycling. Consequently 40 mm joints are not recommended for use in aerial applications.

13) Ageing of aramid material has shown strength loss to increase with temperature and ageing medium concentration. It is not clear how much of the recorded strength loss is due to true material strength loss and how much is due to increased fibre disorder and reduced load sharing.

14) Mineral oils have very little effect on the tensile strength of aramid. Ultra violet radiation has been shown to affect aramid to a lesser extent than non saline ionic solutions, and is accompanied by discolouration to a brown or deep amber colour.

15) Sheath repair may be required on duct cables that are to be reinstalled or aerial cables generally. The precise nature of any ageing will need to be assessed for each cable environment.

16) Dyneema is generally resistant to chemical ageing. Dyneema lacks resistance to thermal and ultra violet radiation. Thermal degradation due to the comparatively low melting temperature of the material creates processing difficulties.

17) Aramid Young's modulus and LASE results show Twaron and Kevlar to be generally insensitive to changes in Young's modulus due to ageing.

18) Aged fatigue test results show that Kevlar, Twaron and Dyneema suffer an increased reduction in material performance due to ageing followed by fatigue testing. The tensile strength reduction was greater than the sum of the ageing and fatigue cycling parts.

19) Aramid will survive in excess of one year of environmental weathering at 0.5% strain in a British type climate where abrasion is eliminated.

20) The two aramid material brands have demonstrated material equivalence. Aramid is suitable for low weight high strength duct, direct buried, internal and aerial communication cable applications. Aramid used in aerial applications should be filled to greatly reduce mechanical abrasion of the continuous fibres.

21) Jointing by the Enka Technica air splice method is recommended for duct, direct buried and internal type cables without technical restriction.

22) E-glass yarn such as the brand tested as part of this project is recommended for duct, internal and direct buried peripheral strength member applications. E-glass is not recommended for aerial applications due to mechanical abrasion and low Tenacity (increased cable weight) considerations.

23) Under no circumstances should UHMWPE be used as the peripheral strength member in aerial cable applications due to high creep behaviour.

7.0 RECOMMENDATIONS FOR FURTHER WORK

1) Test for differences in mechanical performance and chemical resistance from a selected batch of aramid bobbins and aramid bobbins from a number of production batches. Bobbin to bobbin variation was not studied as part of this investigation but has been reported by other workers [10,11]

2) Conduct cable creep tests on proprietary span lengths of aerial cable using an optical strain fibre or other technique. This is suggested as a means of investigating gauge length dependencies, and also to identify whether creep is uniform over the whole length of the suspended cable span.

3) Conduct aeolian and galloping fatigue tests on proprietary span lengths of aramid stranded cable before subjecting the cables to tensile testing on a cable (150 m) test rig. This with a microscopical investigation of the aramid strength members at points of stress concentration would clarify the prediction based on laboratory fatigue tests that abrasion of the aramid strength members upon fatigue cycling leads to aramid fibre failure and cable strength reduction.

4) Conduct LASE and creep tests on long (150 m) samples of aramid stranded cable containing jointed aramid on a cable test rig, for comparison with LASE test data for cables of the same design that do not contain joints. This testing would give a better understanding of the gauge length dependence of the tensile performance of joints in cables.

5) Conduct tests on existing cable strength members and develop a correlation between actual and laboratory ageing lifetimes. This would give the acceleration factors that occur in laboratory ageing testing and so allow material lifetime predictions.

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Figure 1 : Aramid Production Scheme

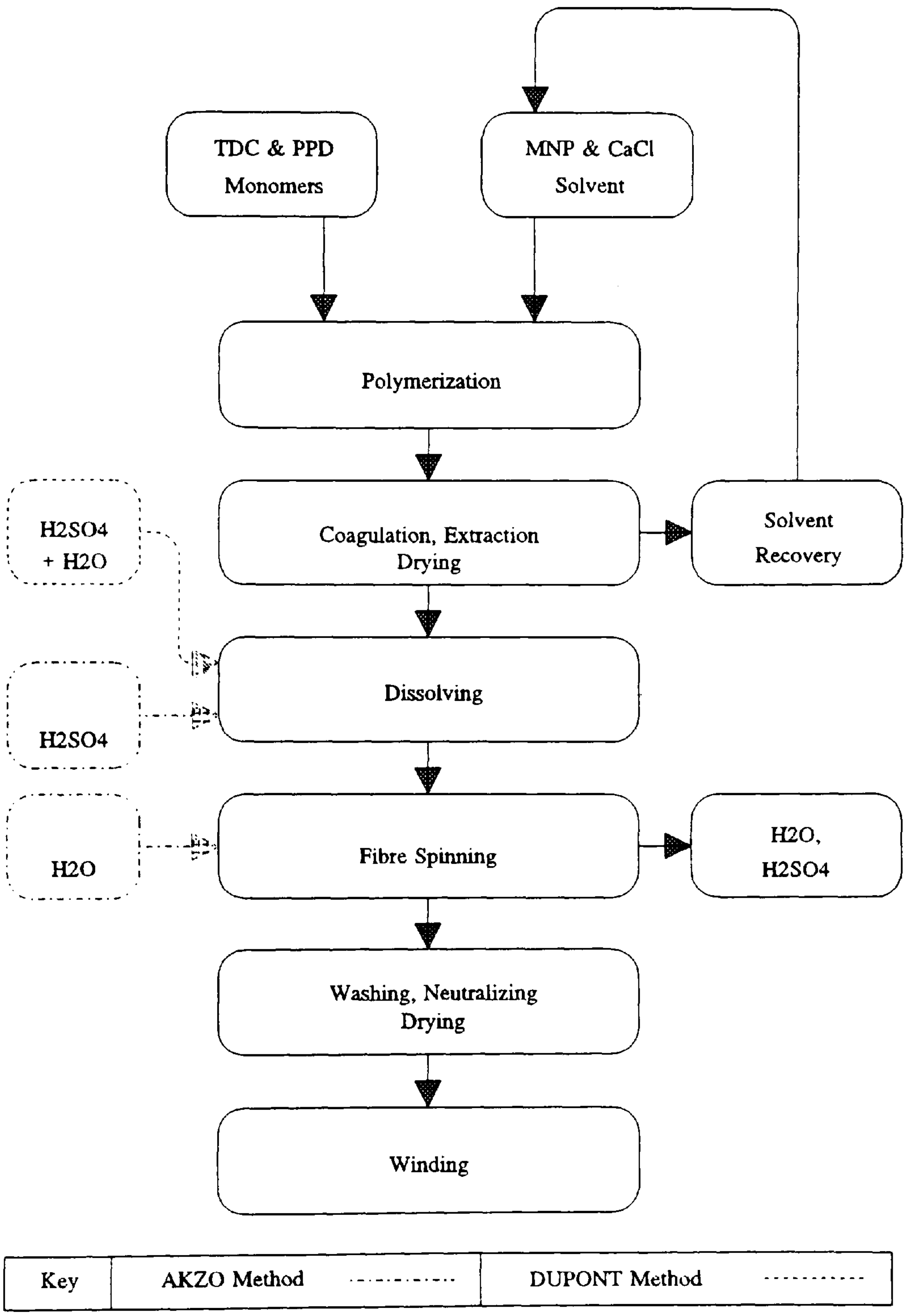


Figure 2 : Creep in Aramid Yarns

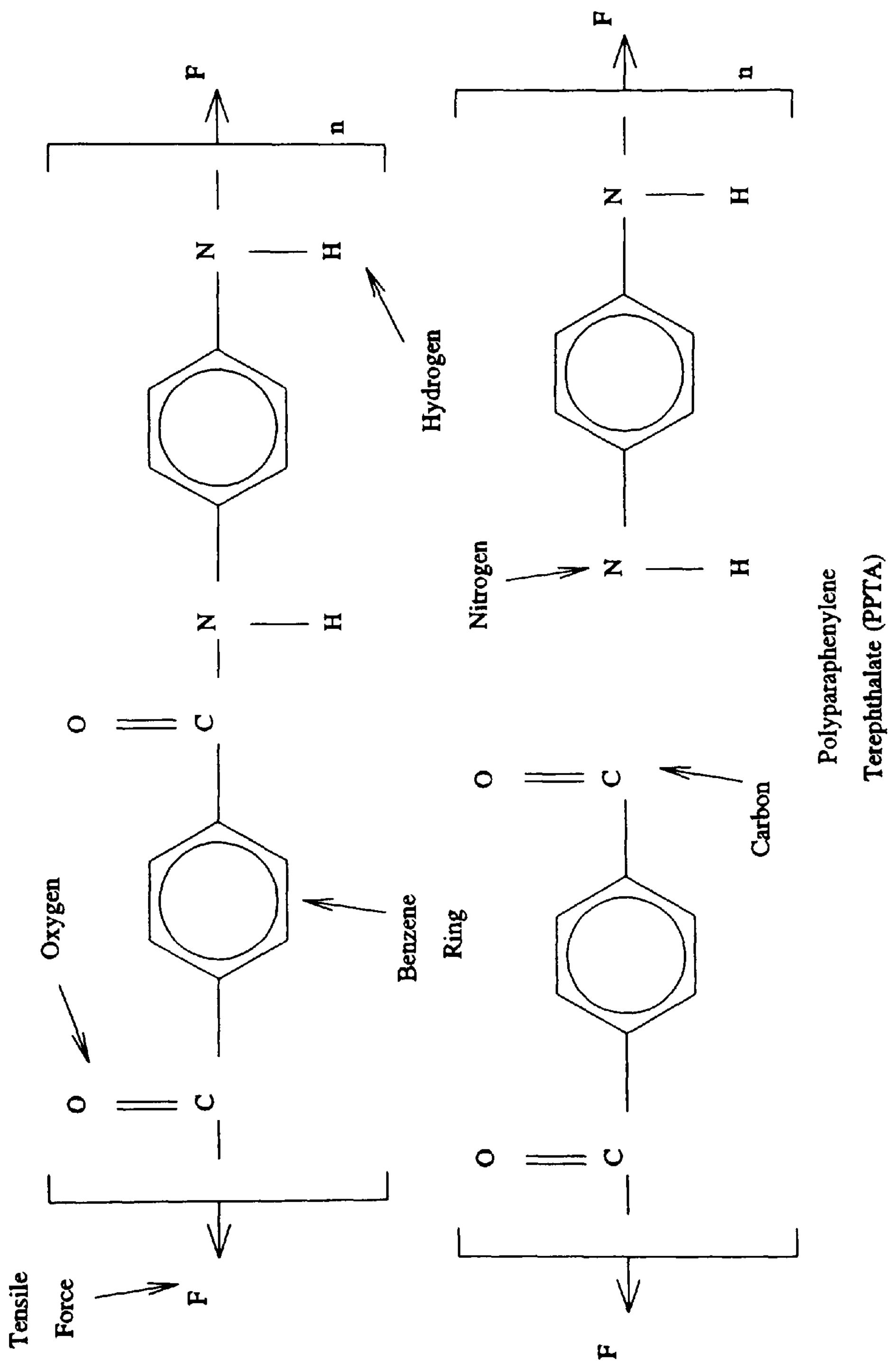


Figure 3 : Creep in UHMWPE

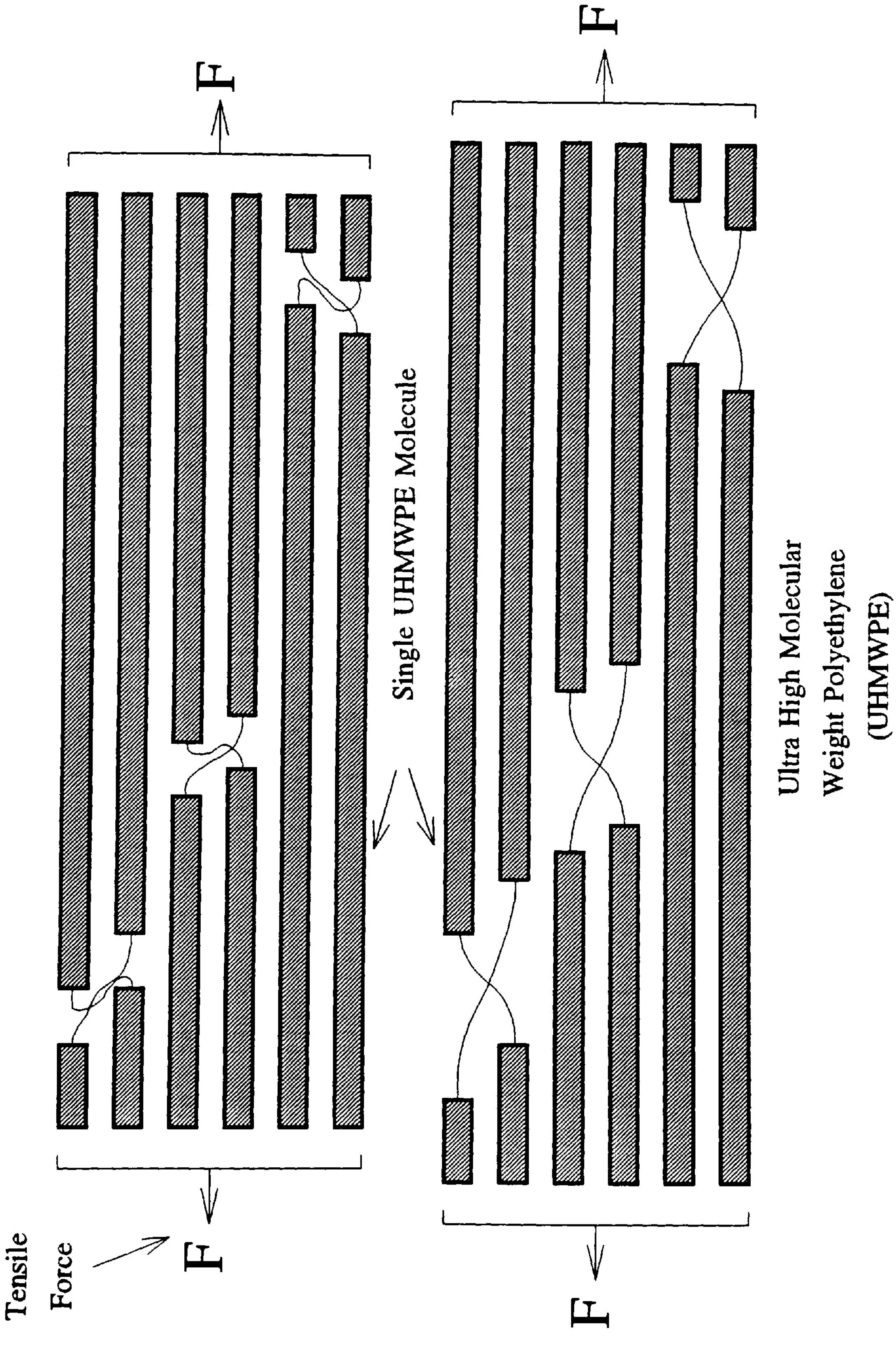


Figure 4 : Yarn General Tensile Test Diagram

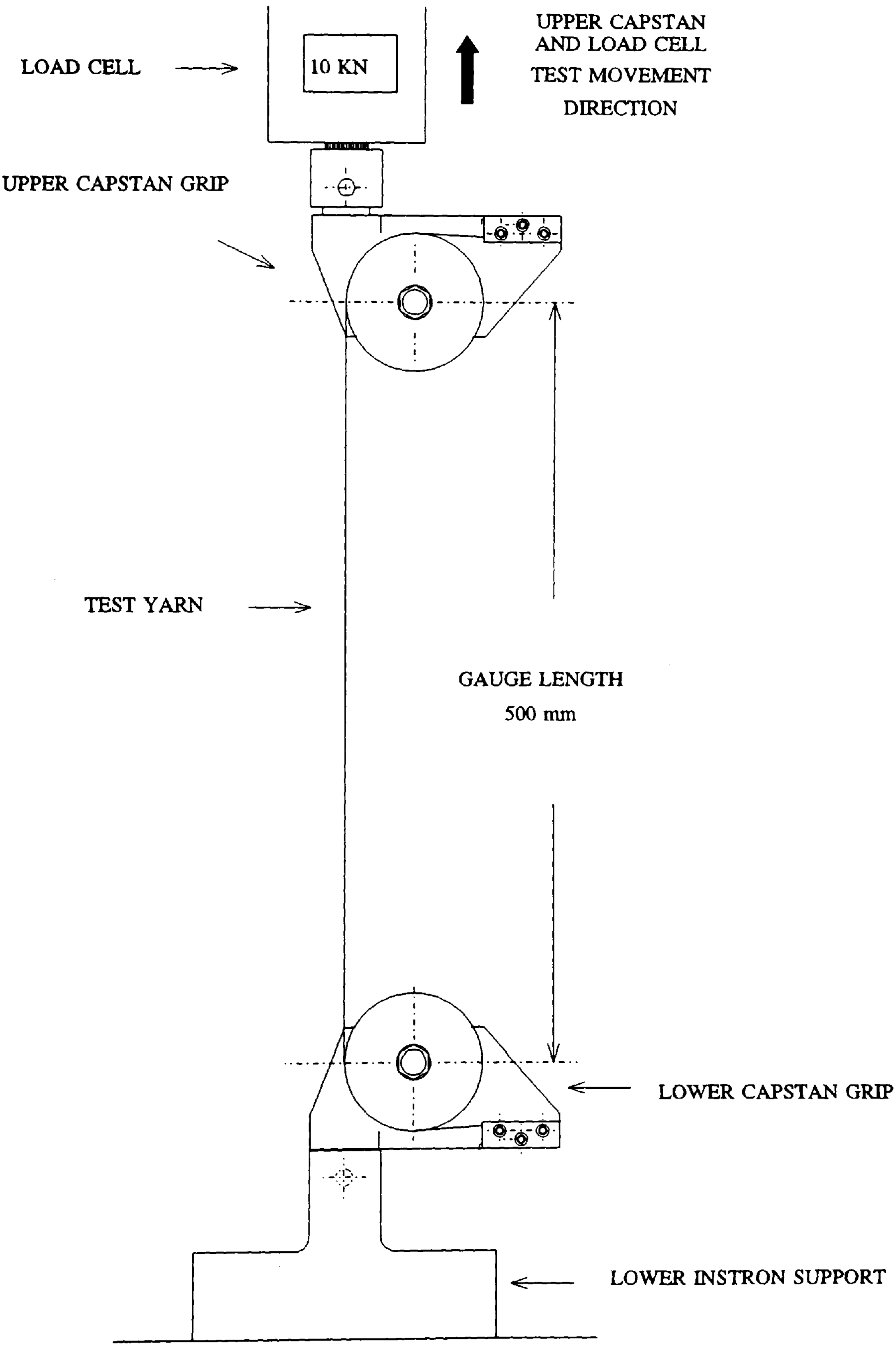


Figure 5 : Yarn LASE Test Diagram

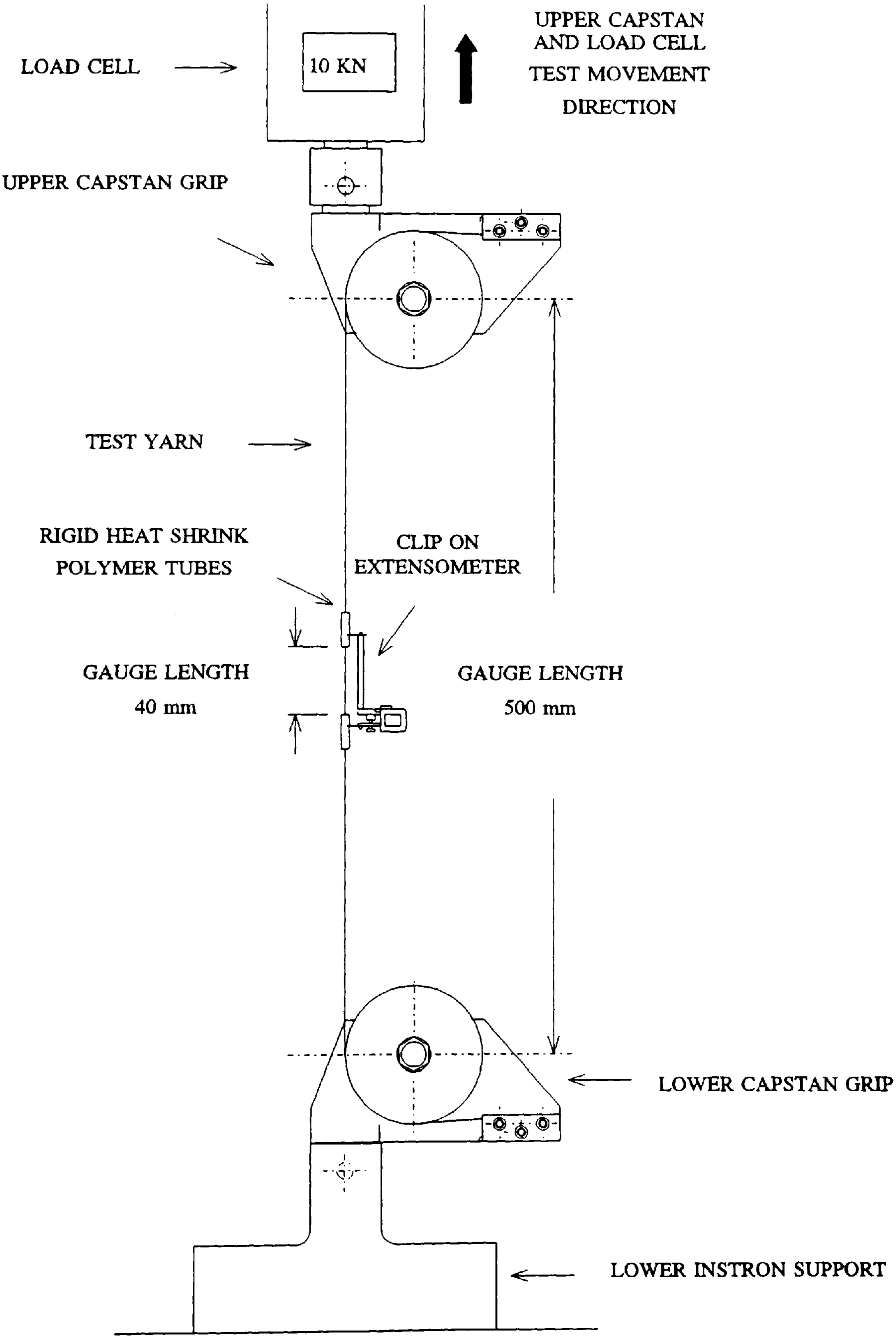


Figure 6 : Cable LASE Test Diagram

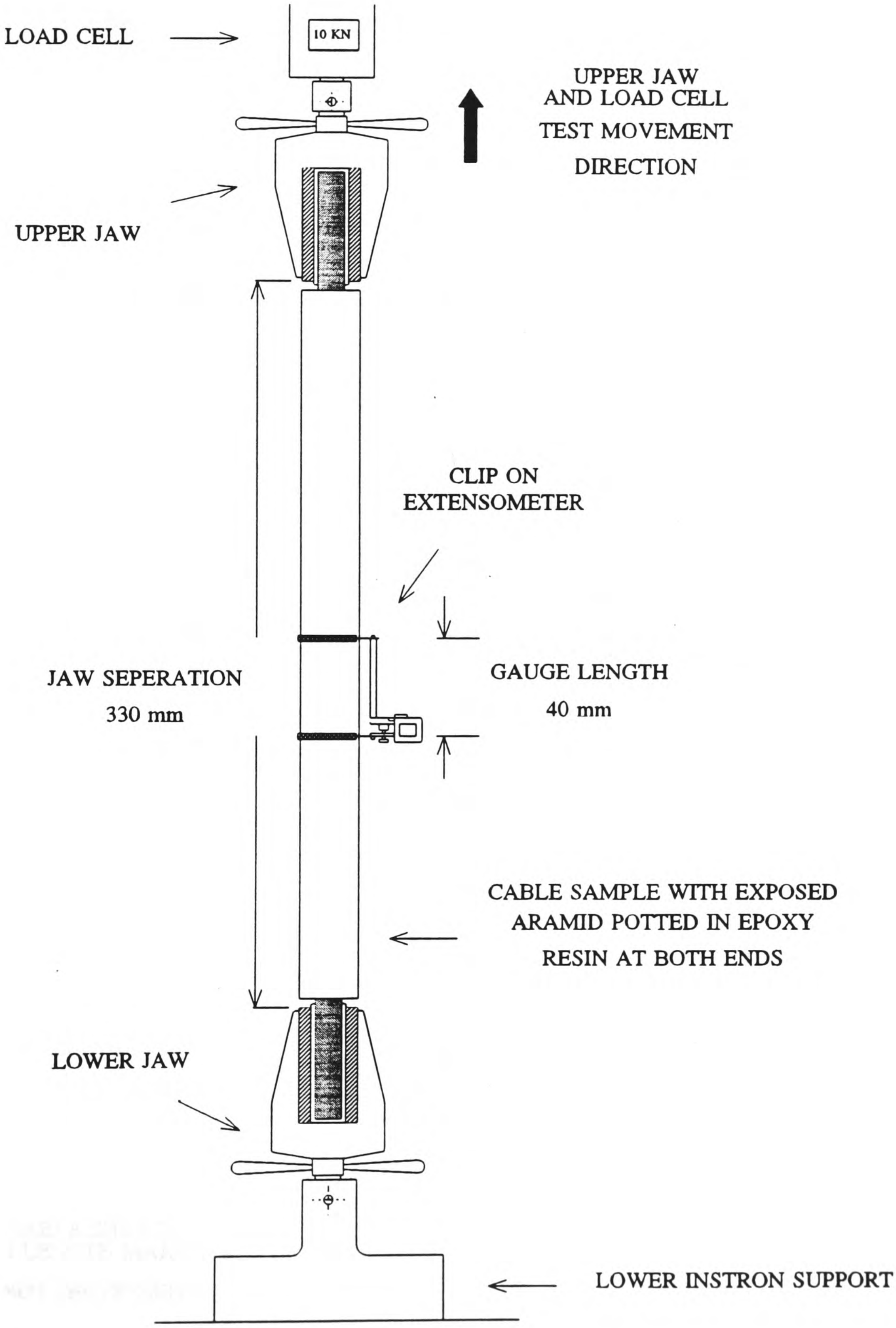


Figure 7 : Cable Epoxy Termination Diagram

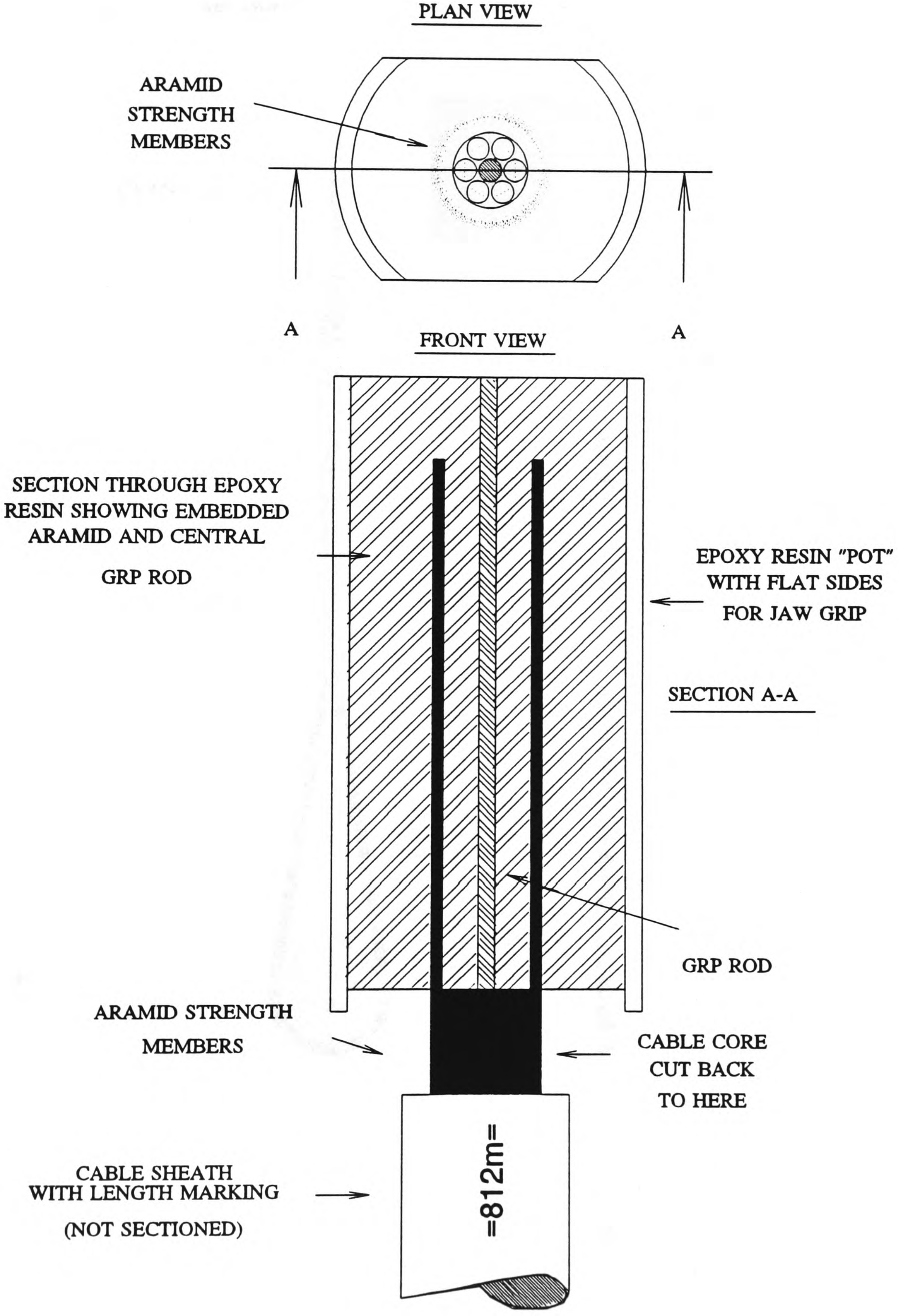


Figure 8 : Yarn Creep Test Terminations

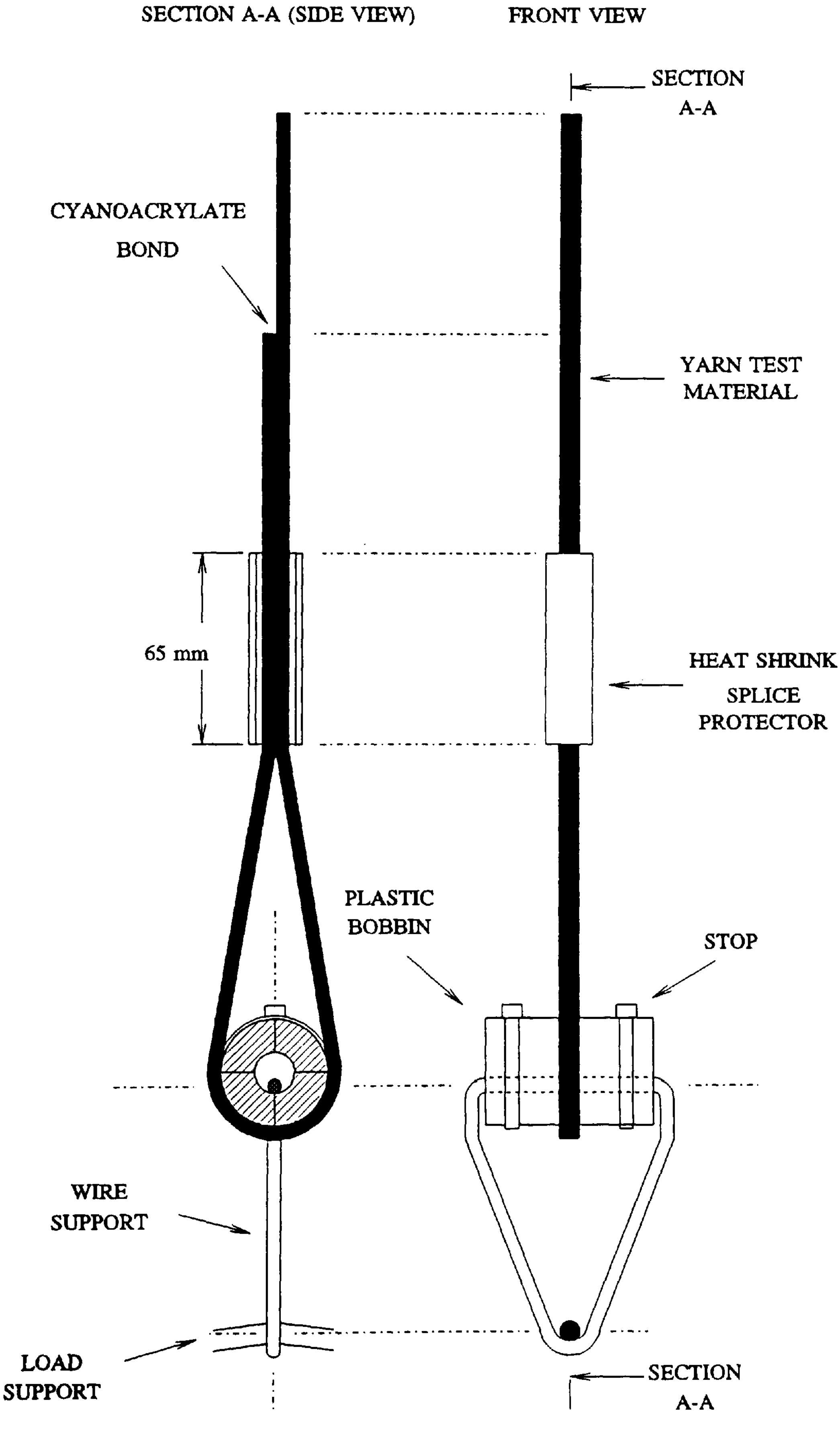


Figure 9 : Yarn Creep Test Measurement Points Diagram

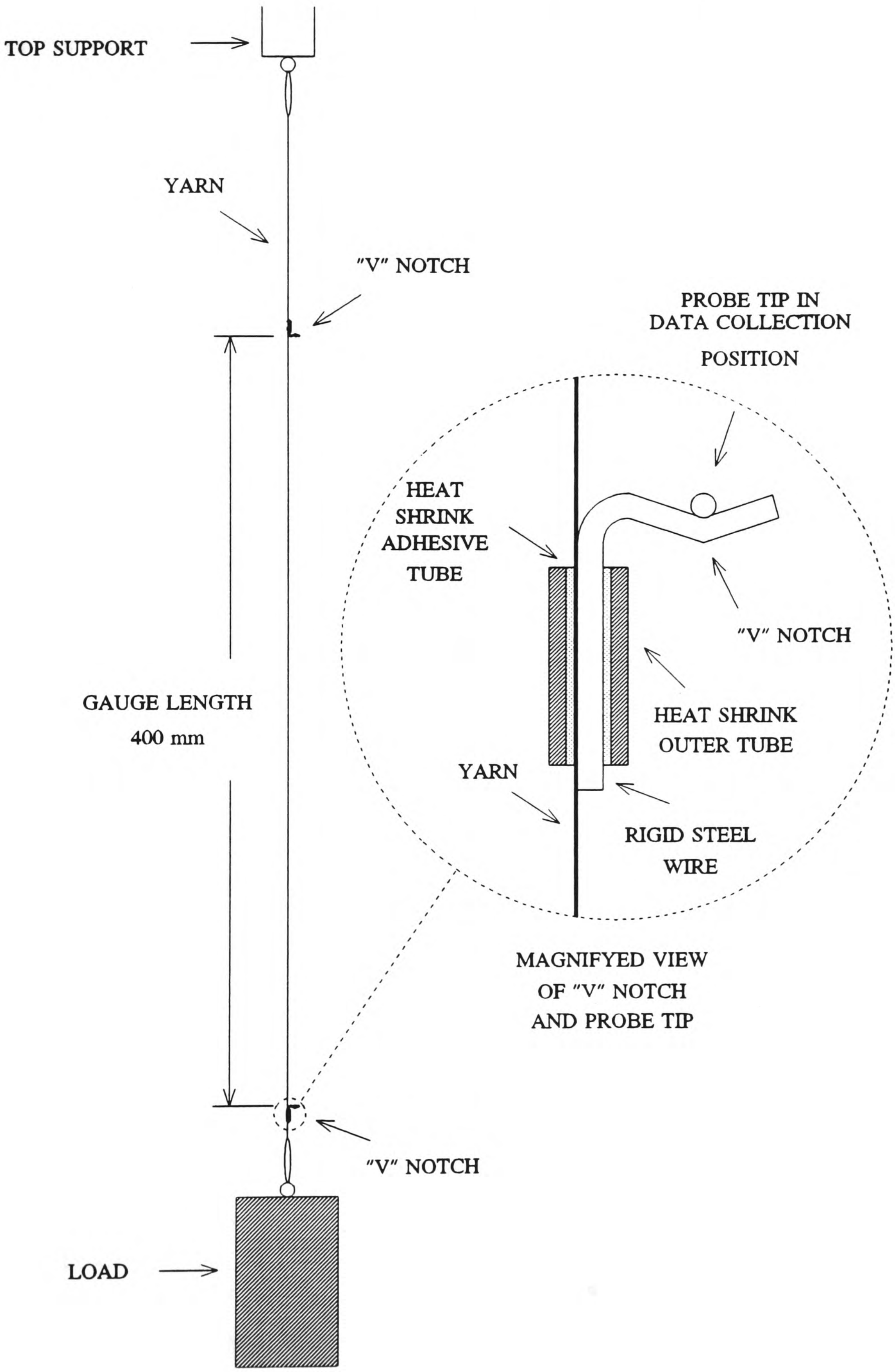


Figure 10 : Yarn Creep Measurement Diagram

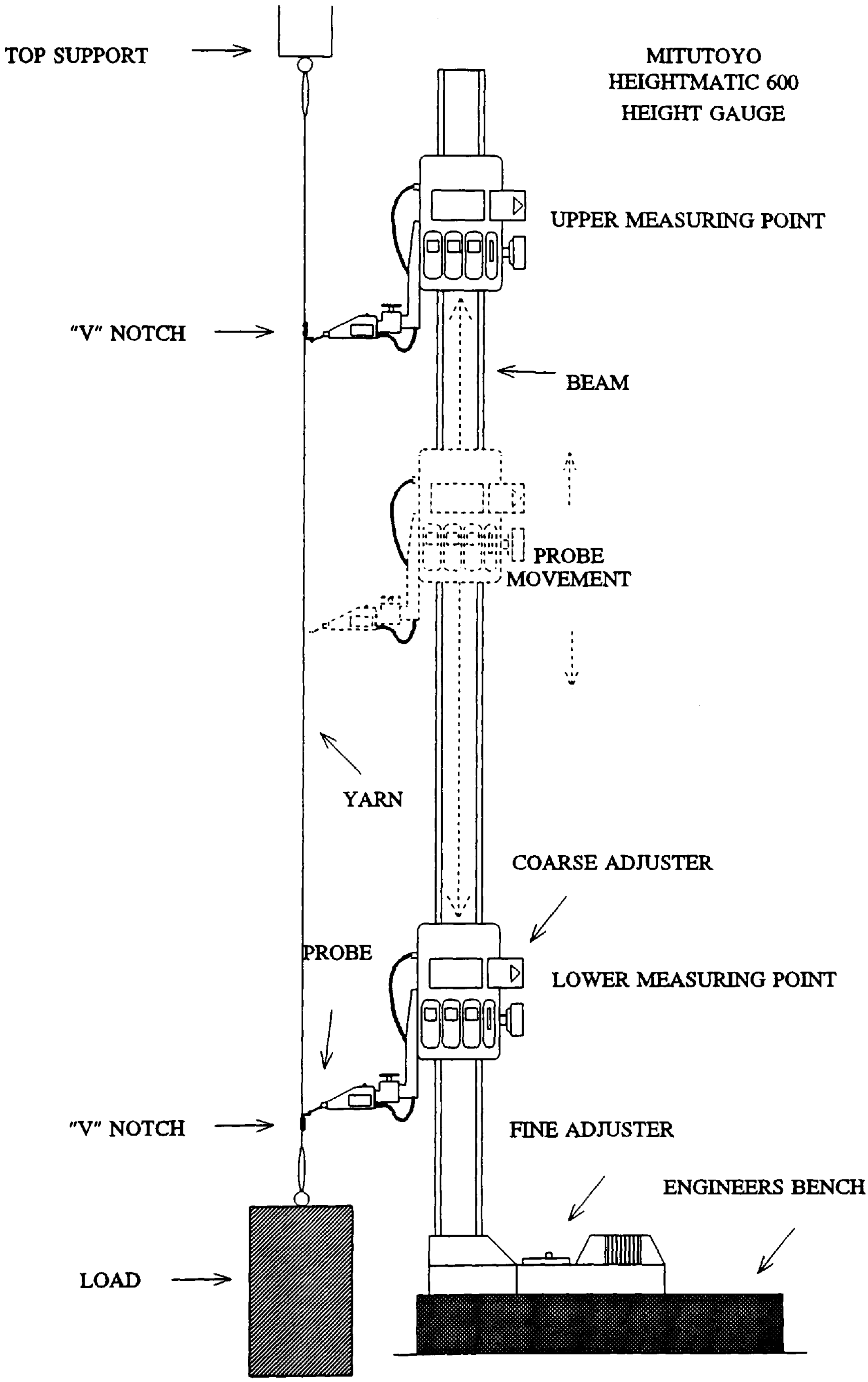


Figure 11 : Yarn Creep Test Support Frame Diagram

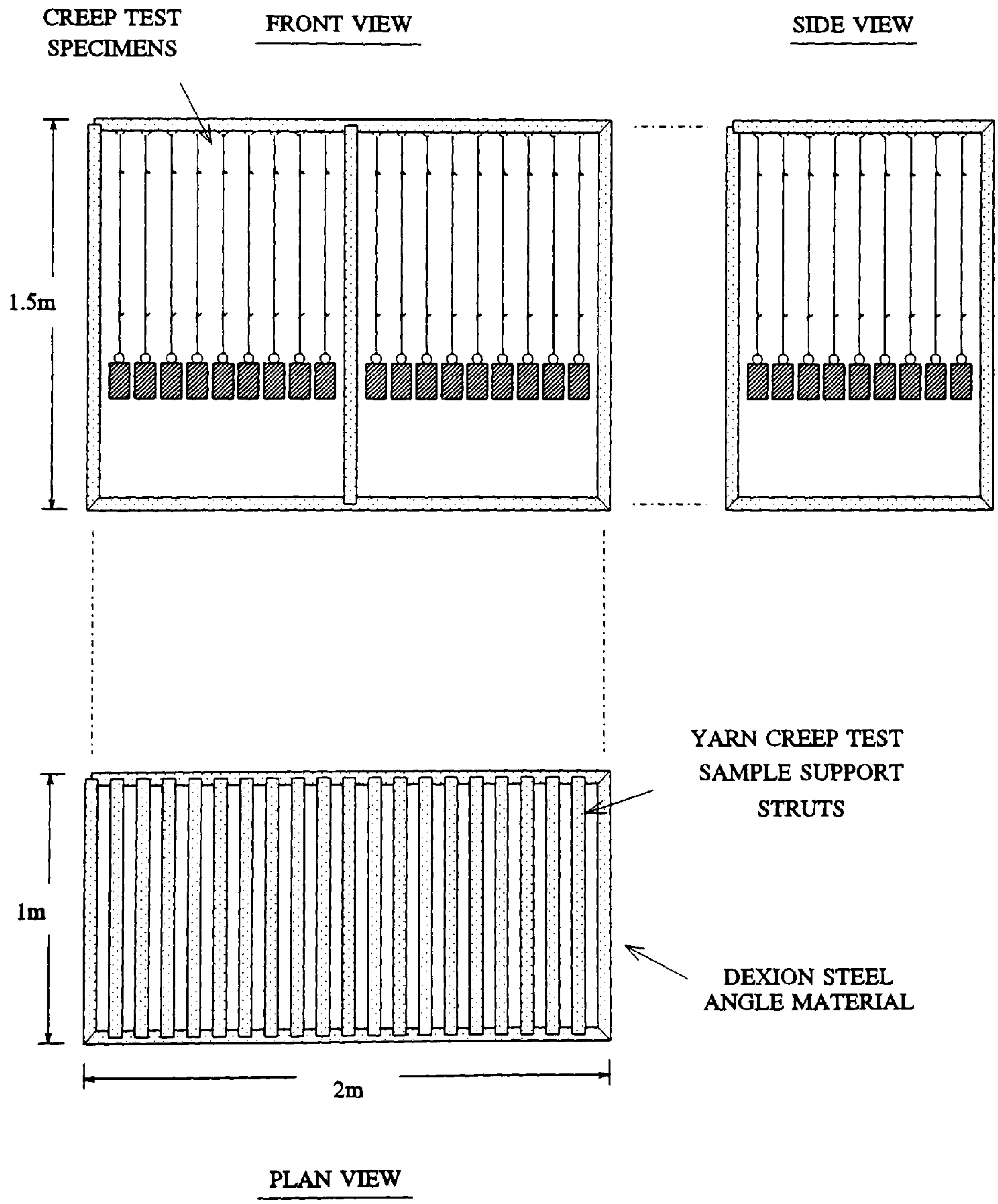


Figure 12 : Cable Creep Test Diagram

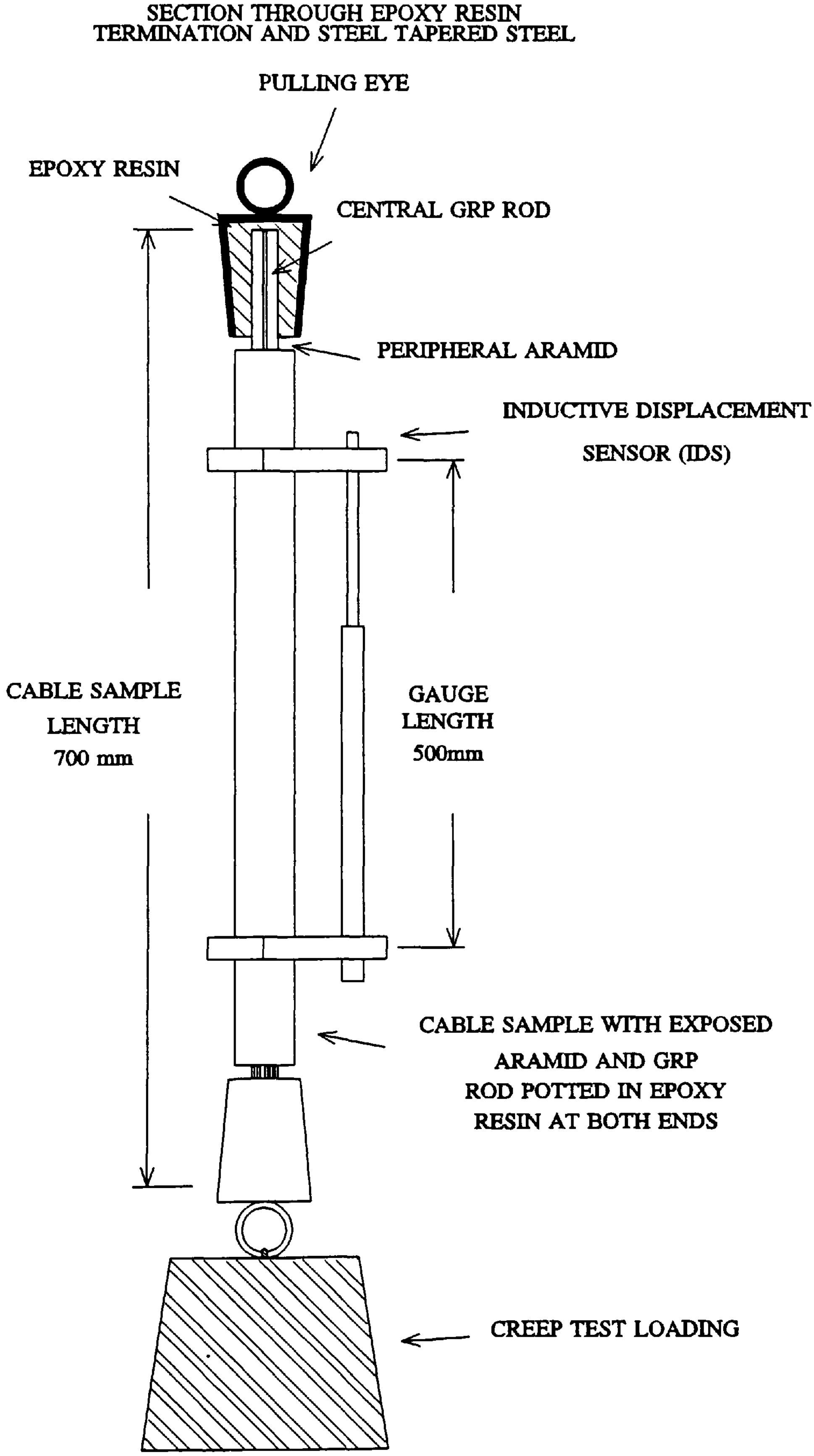


Figure 13 : Yarn Fatigue Test Diagram

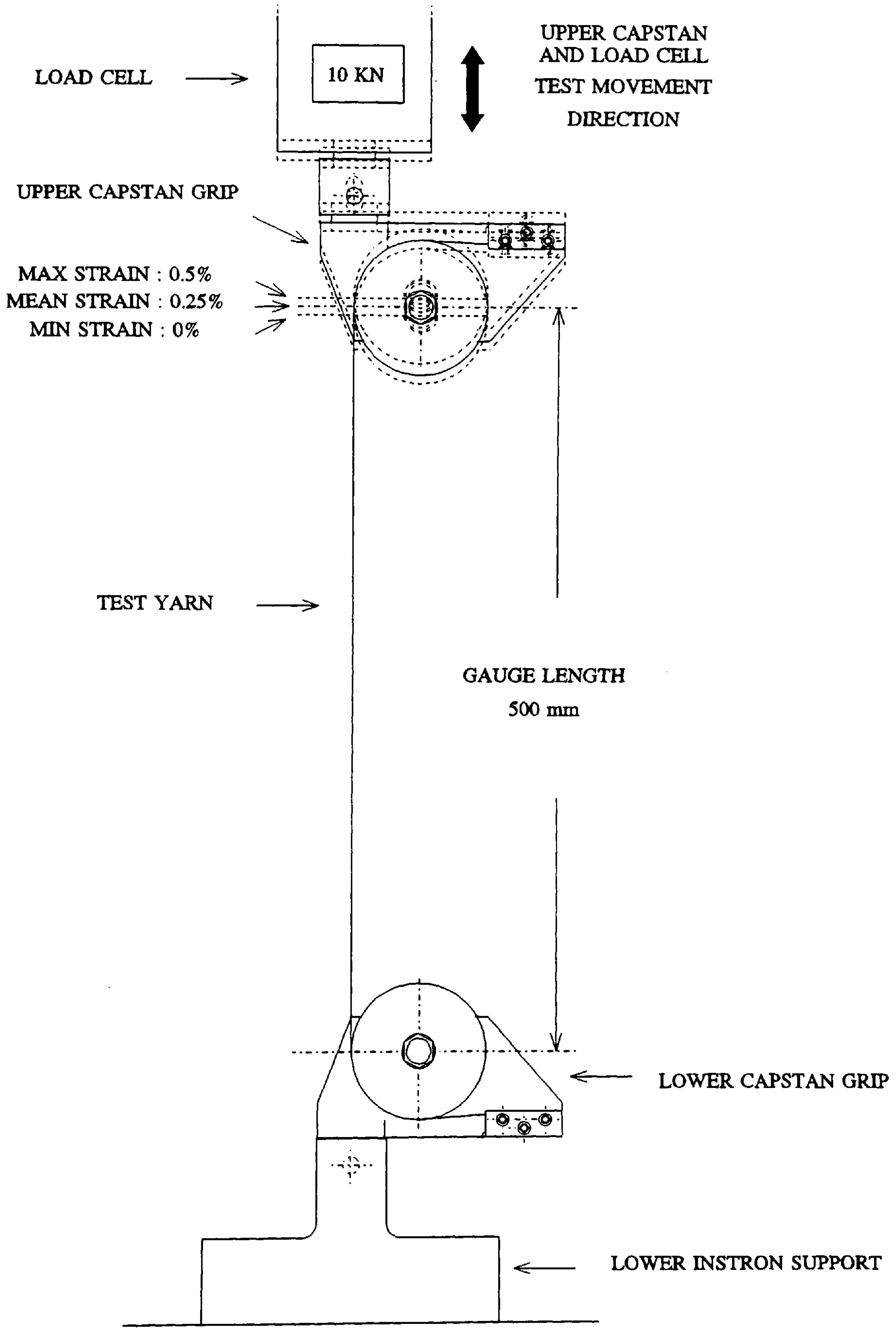
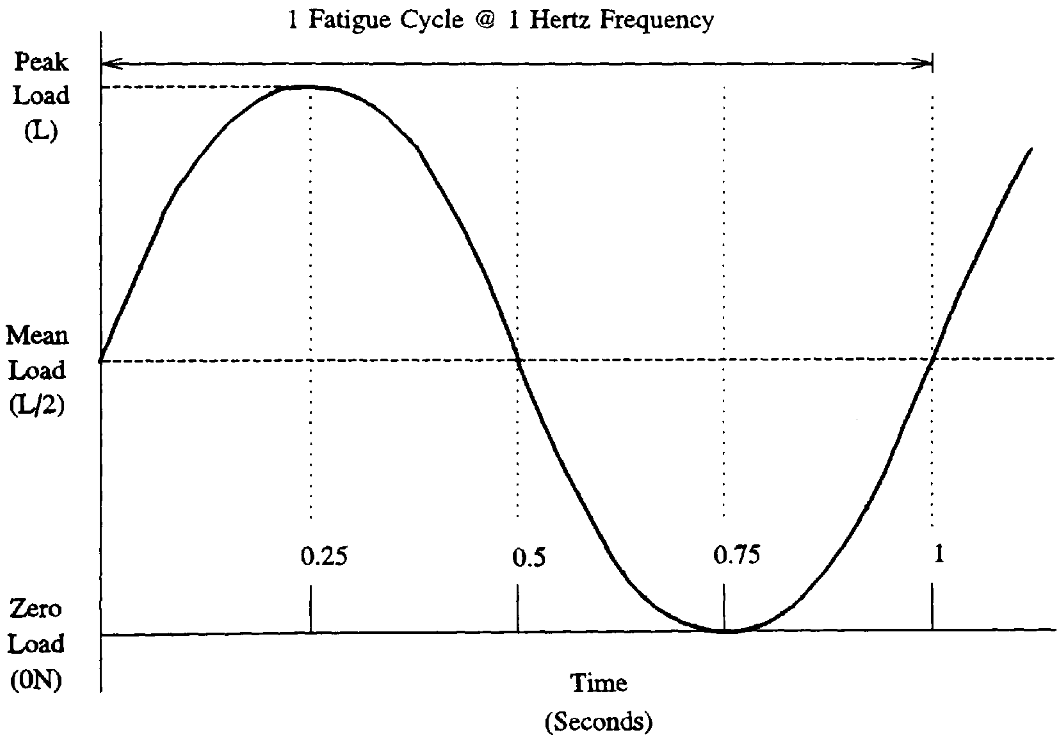


Figure 14 : Fatigue Test Cycle Diagram



L = 62N for DuPont Kevlar 49 & Jointed Kevlar 49 (1580 dtex)

L = 63N for Akzo Twaron Type 1055 (1610 dtex)

L = 66N for DSM Dyneema SK65 (1760 dtex)

L = 88N for Owens Corning OFY 680 (7294 dtex)

Figure 15 : Material Chemical Ageing Schematic

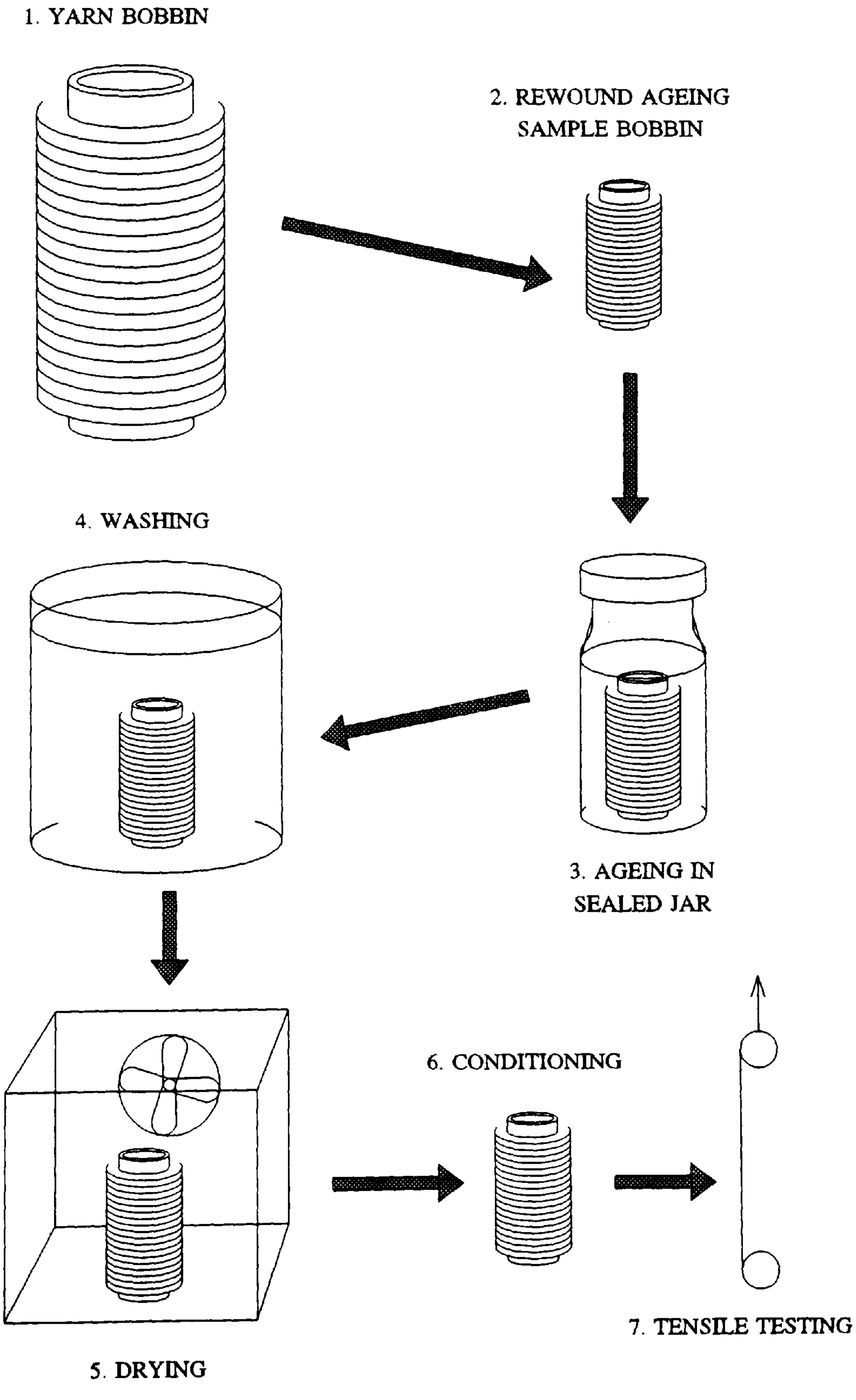


Figure 16 : Material Thermal Ageing Schematic

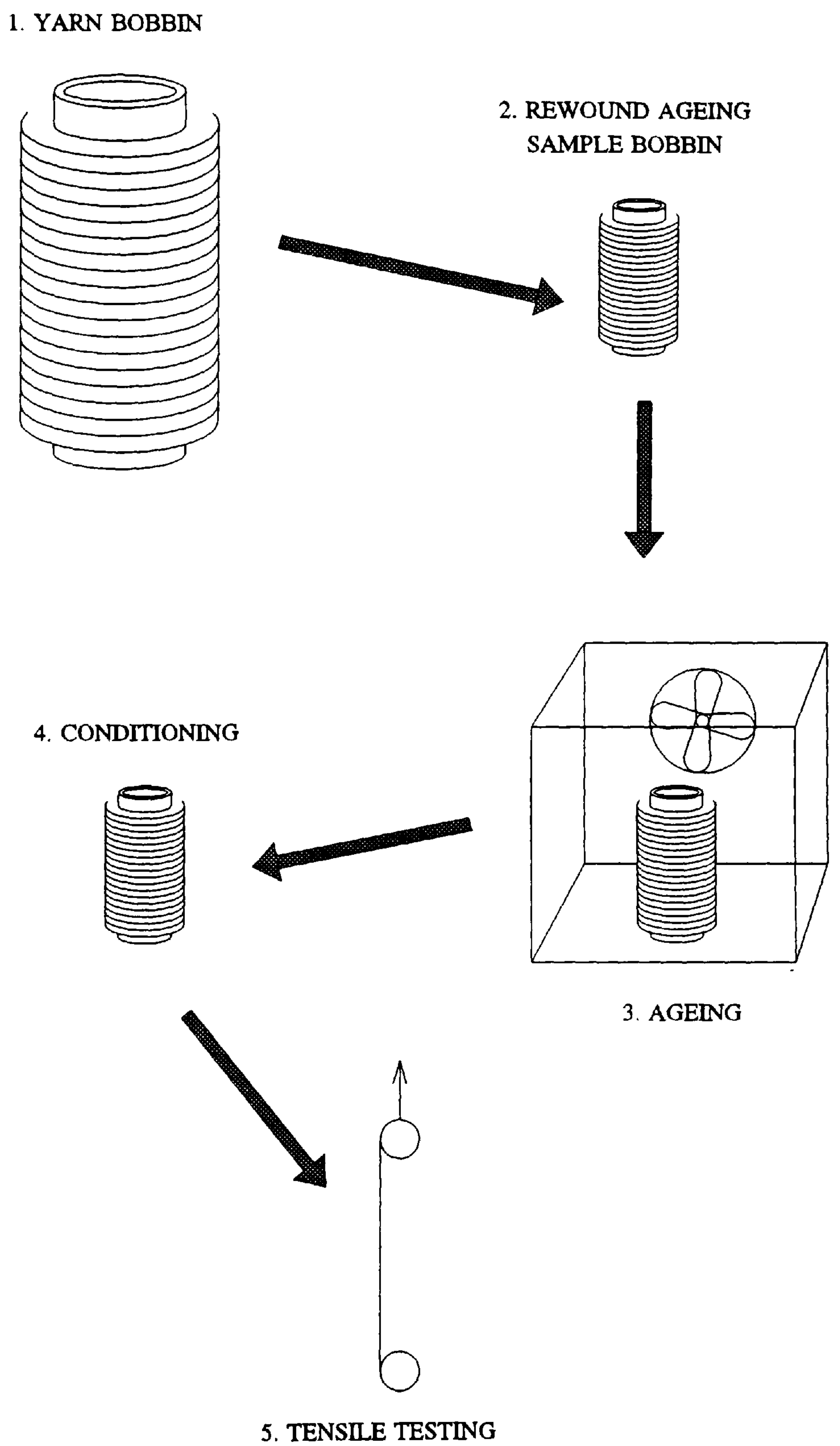


Figure 17 : Material Ultra Violet Ageing Schematic

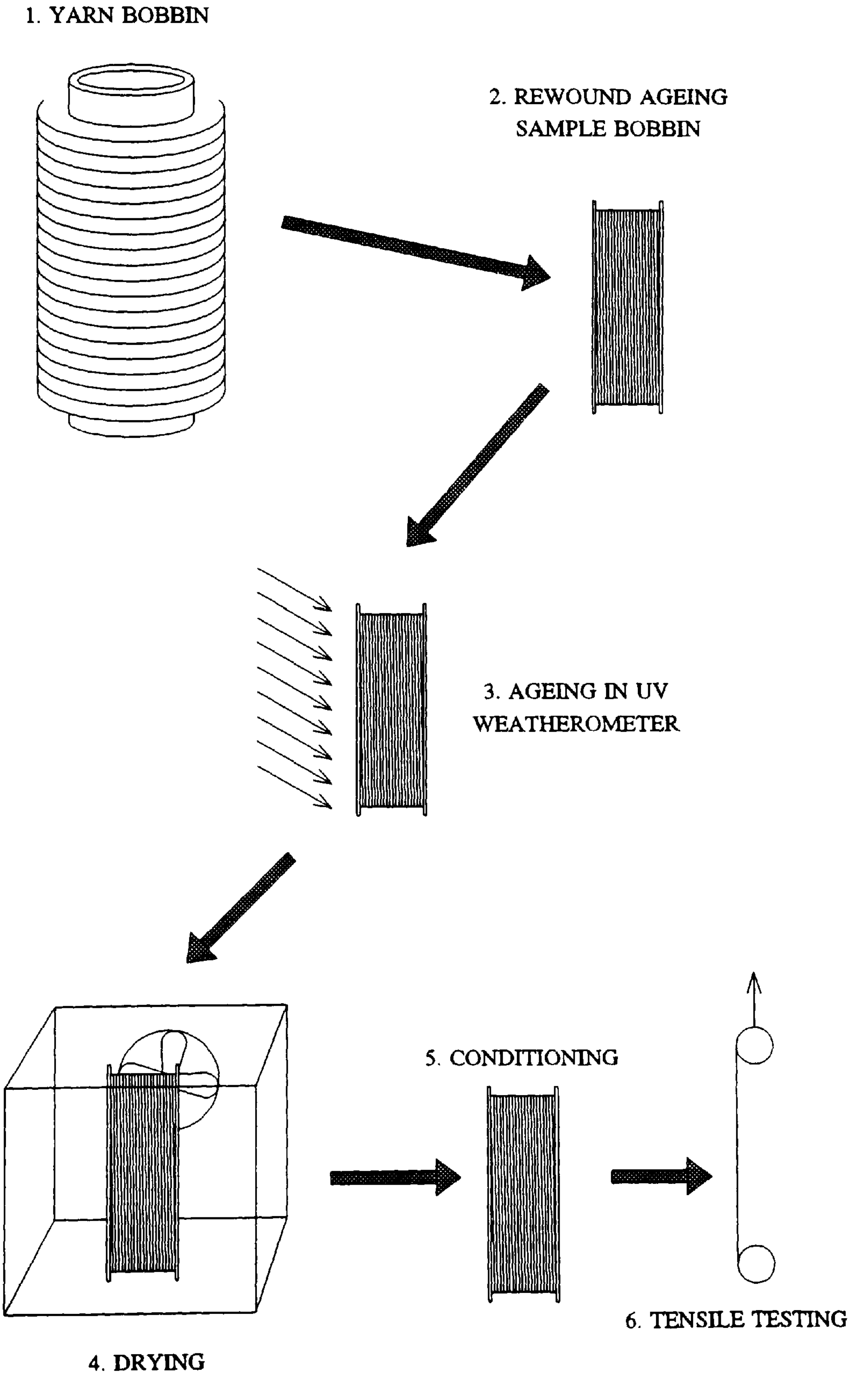


Figure 18 : Material Petrol and Diesel Ageing Schematic

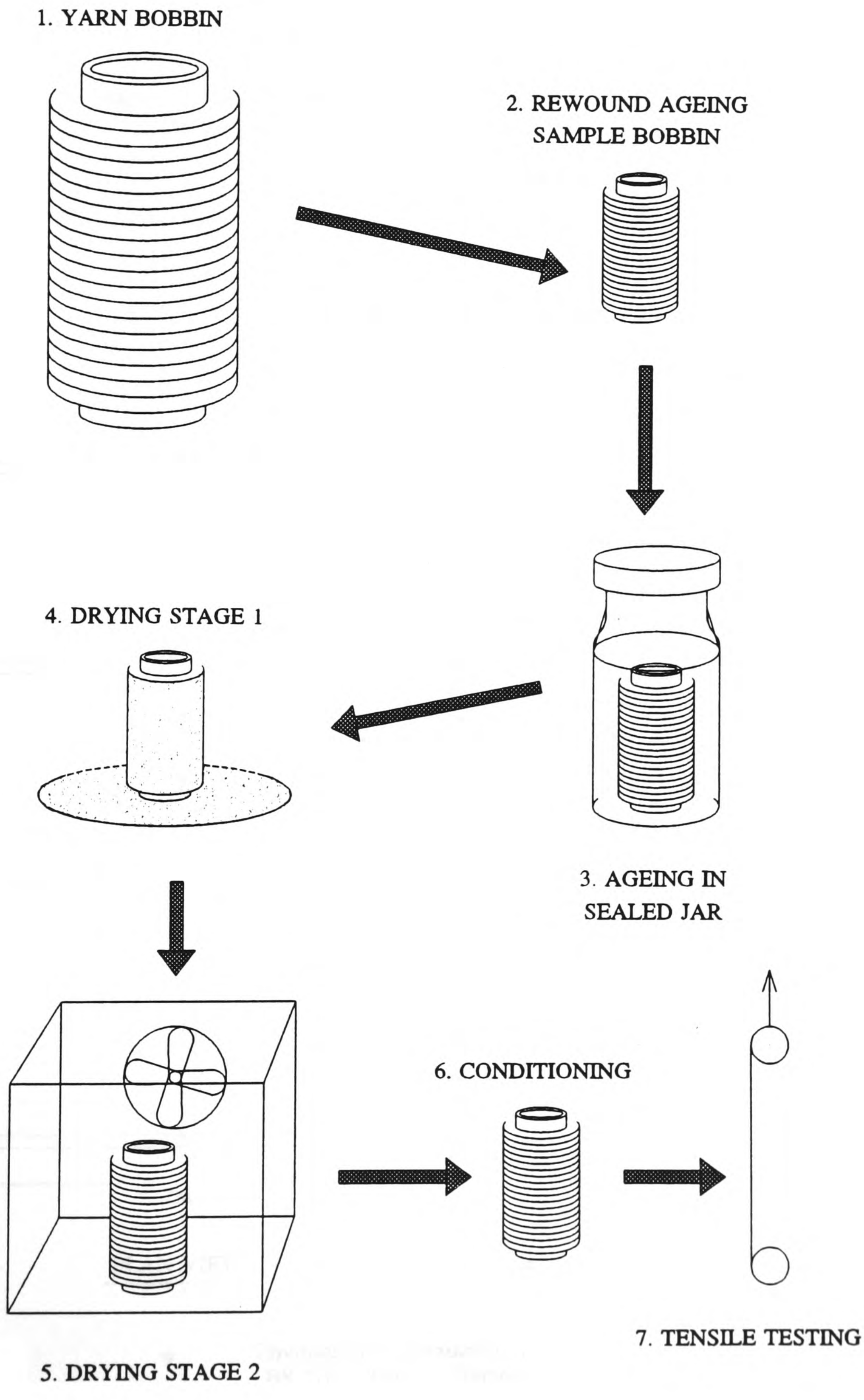
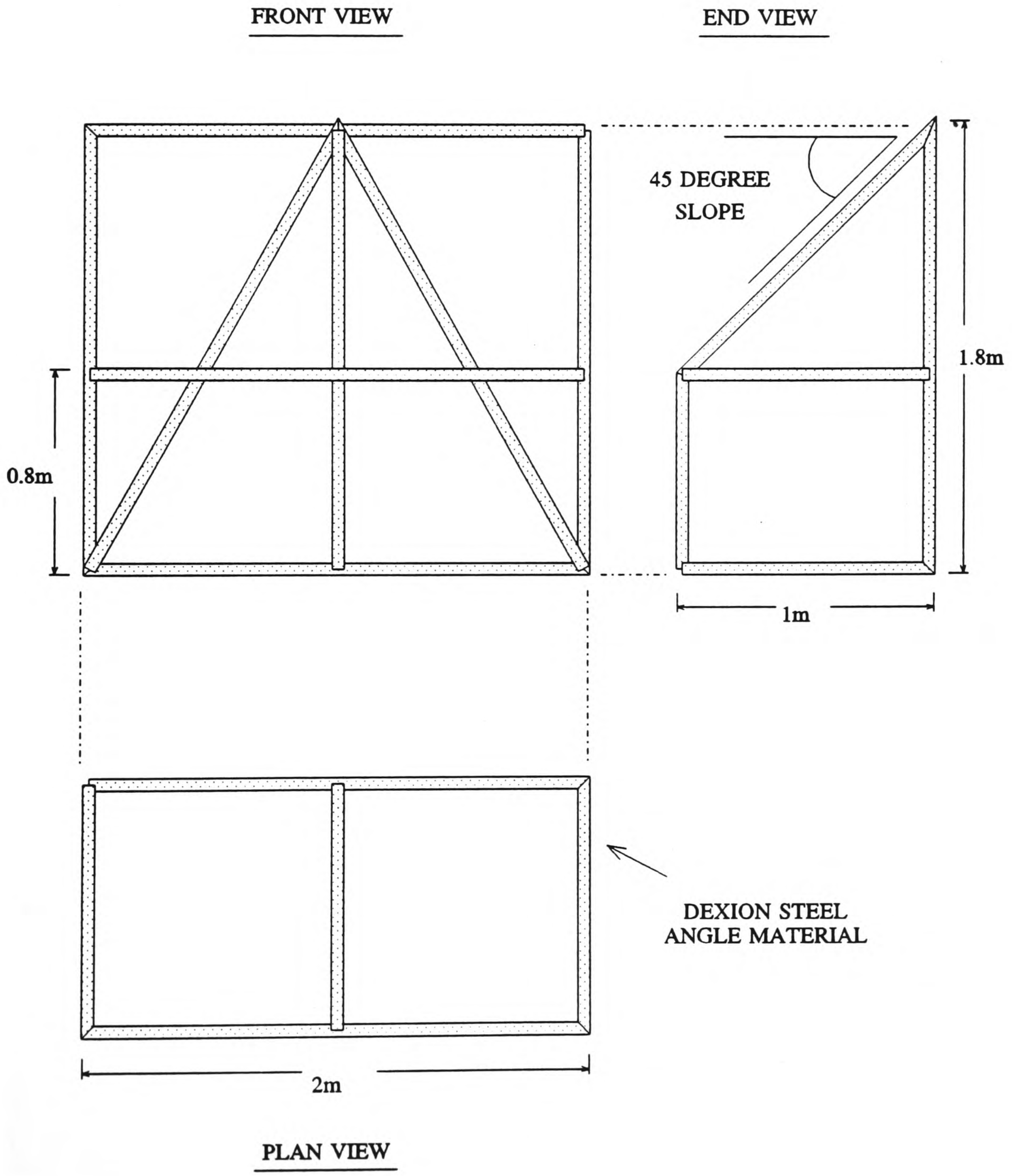


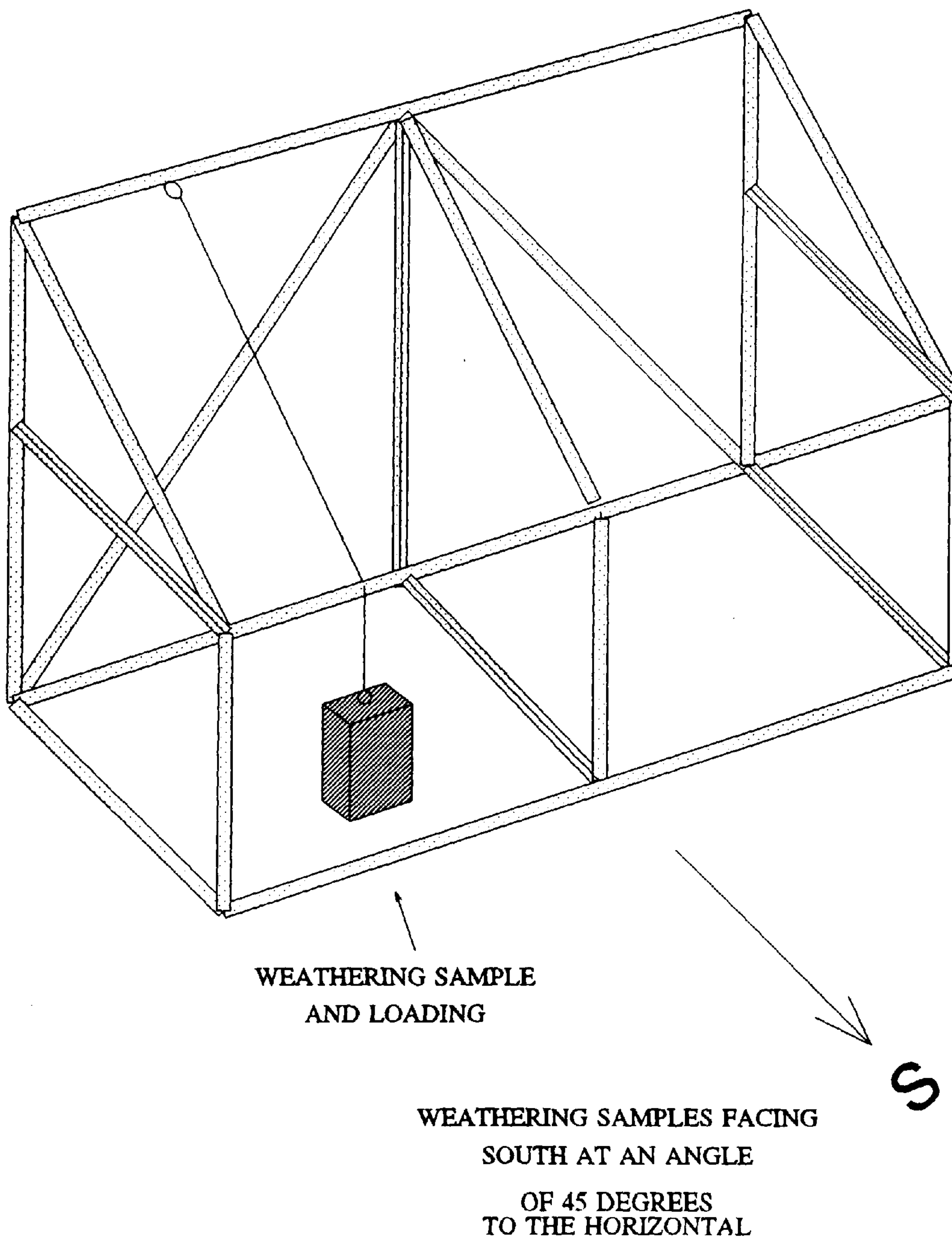
Figure 19 : Environmental Weathering Test Support Frame Diagram



Environmental Weathering Frame to
BS 2782 : Part 5 : Method 550A.

Figure 20 : Environmental Weathering Test

Support Frame Isometric Diagram



Environmental Weathering Frame to
BS 2782 : Part 5 : Method 550A.

Figure 21 : Jointing Equipment Diagram

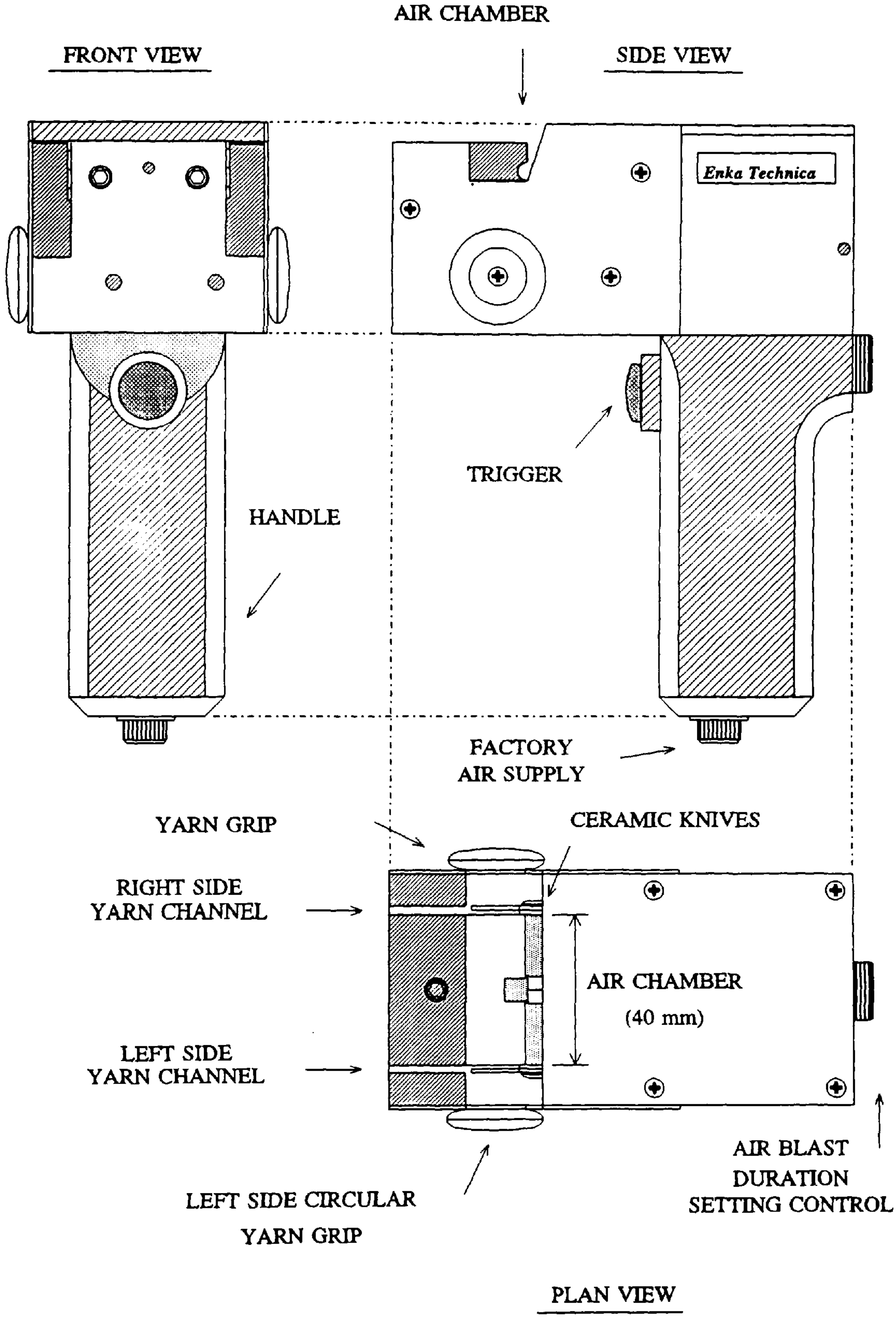


Figure 22 : Jointing Schematic Diagram

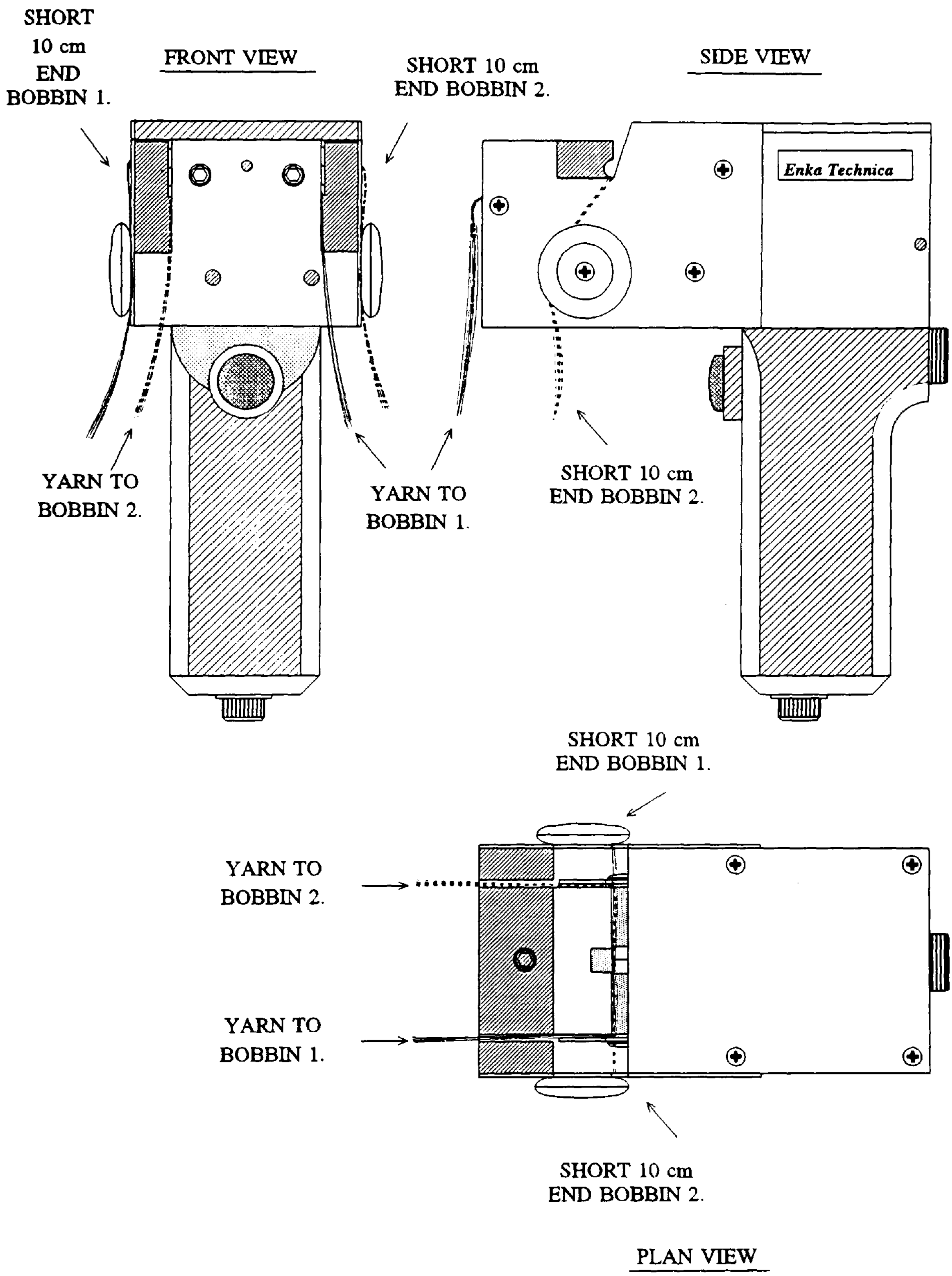


Figure 23 : Tensile Test Results

For AKZO Twaron Type 1055 (1610 dtex).

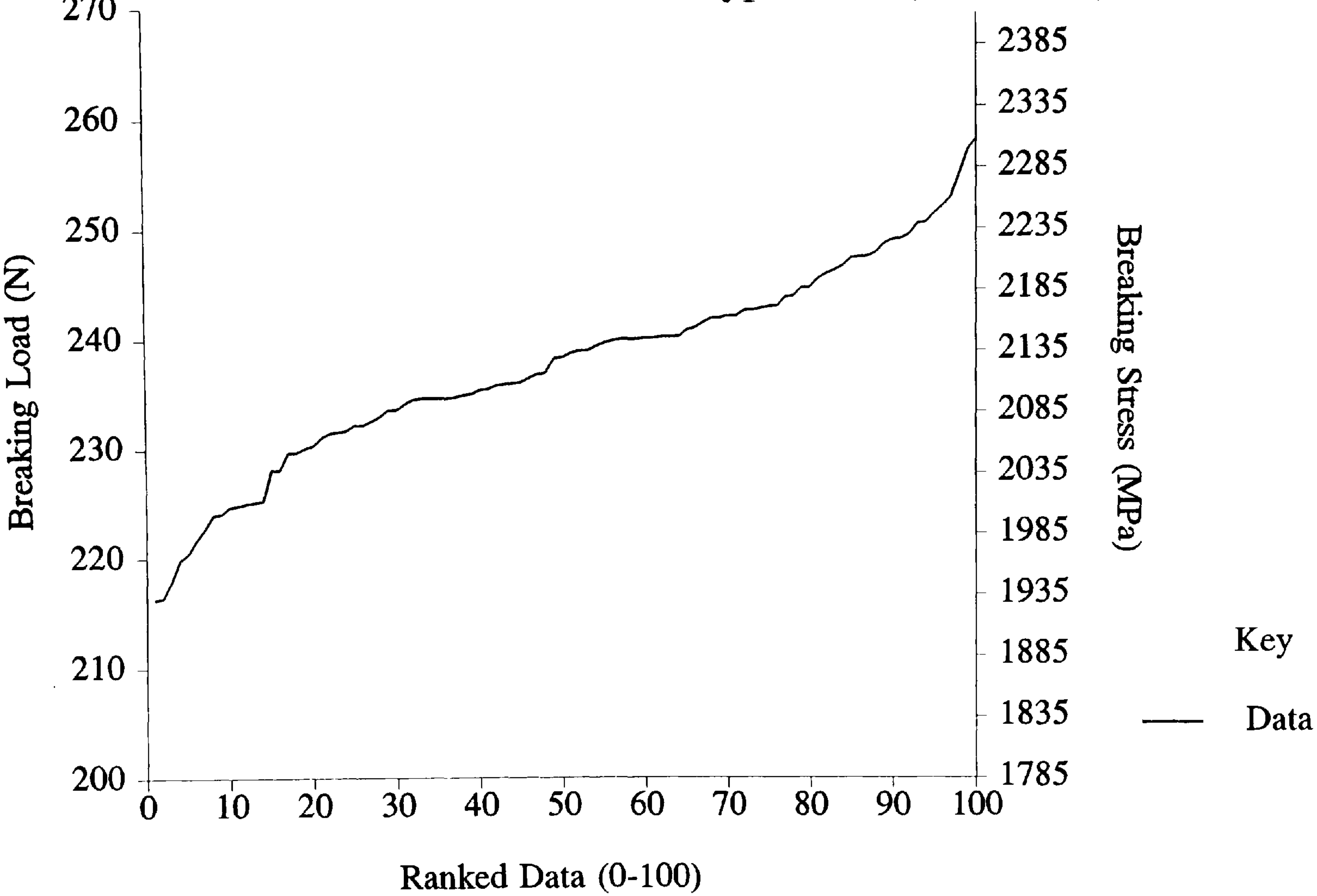


Figure 24 : Tensile Test Results
For DuPont Kevlar 49 (1580 dtex).

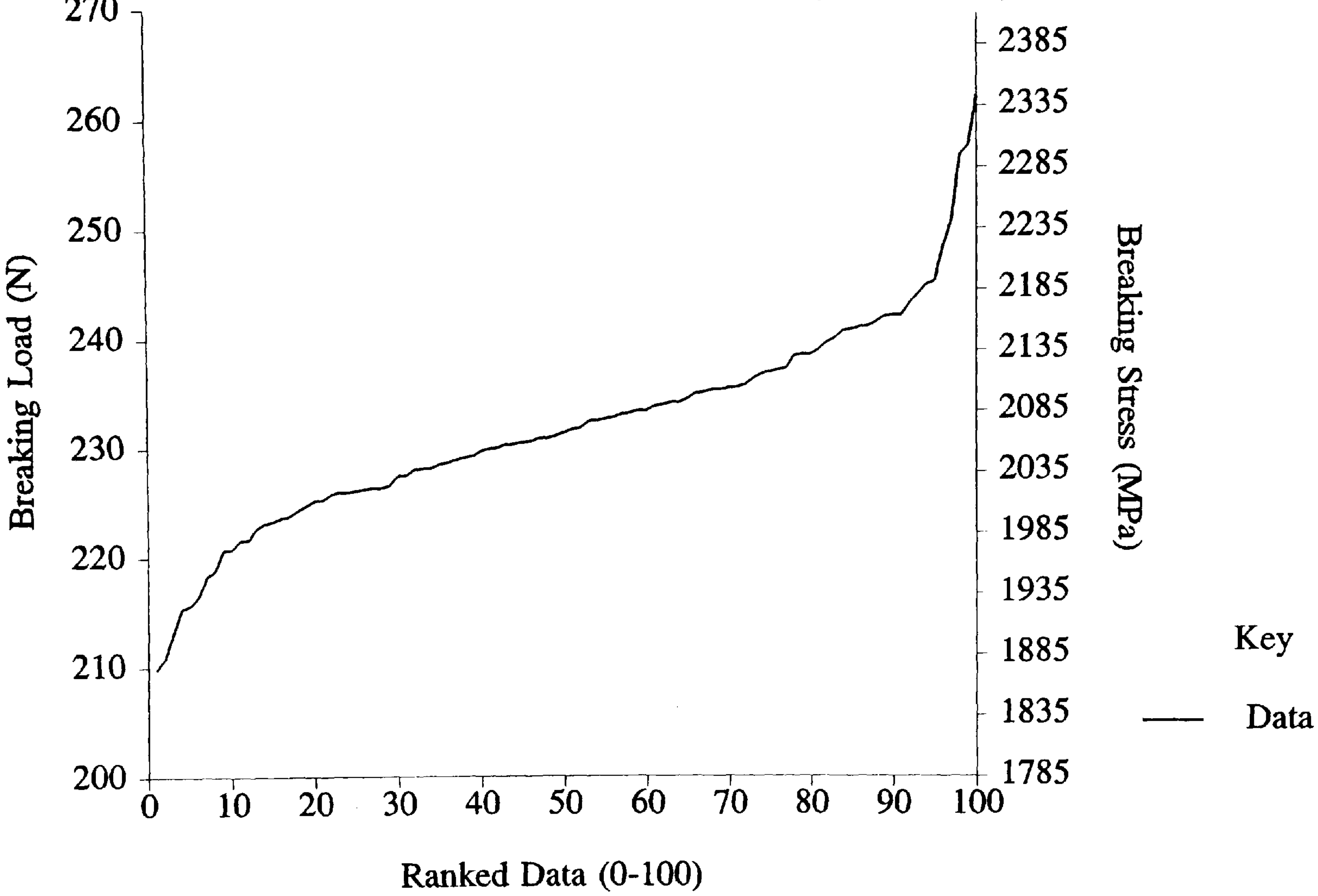
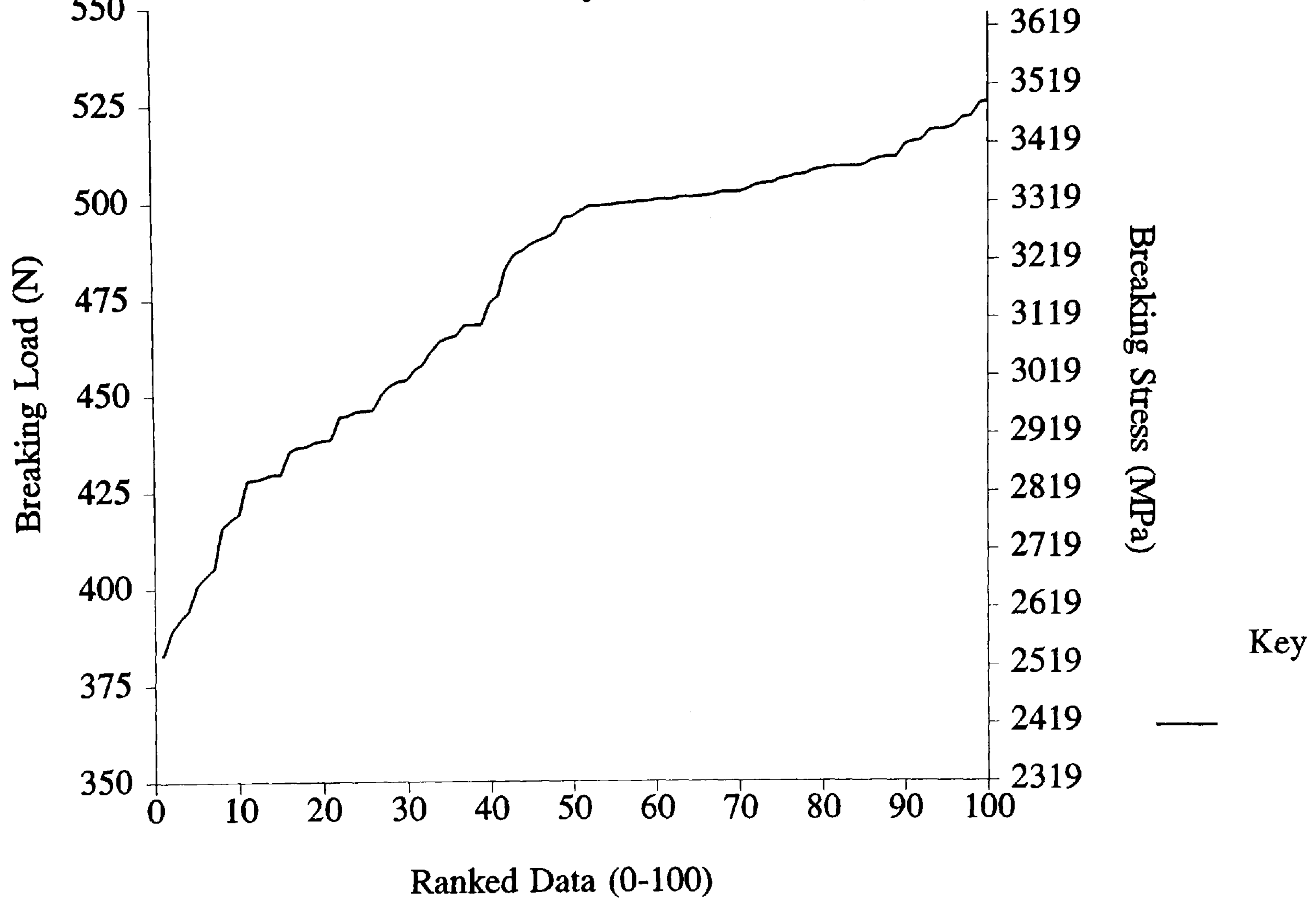


Figure 25 : Tensile Test Results

For DSM Dyneema SK65 (1760 dtex).



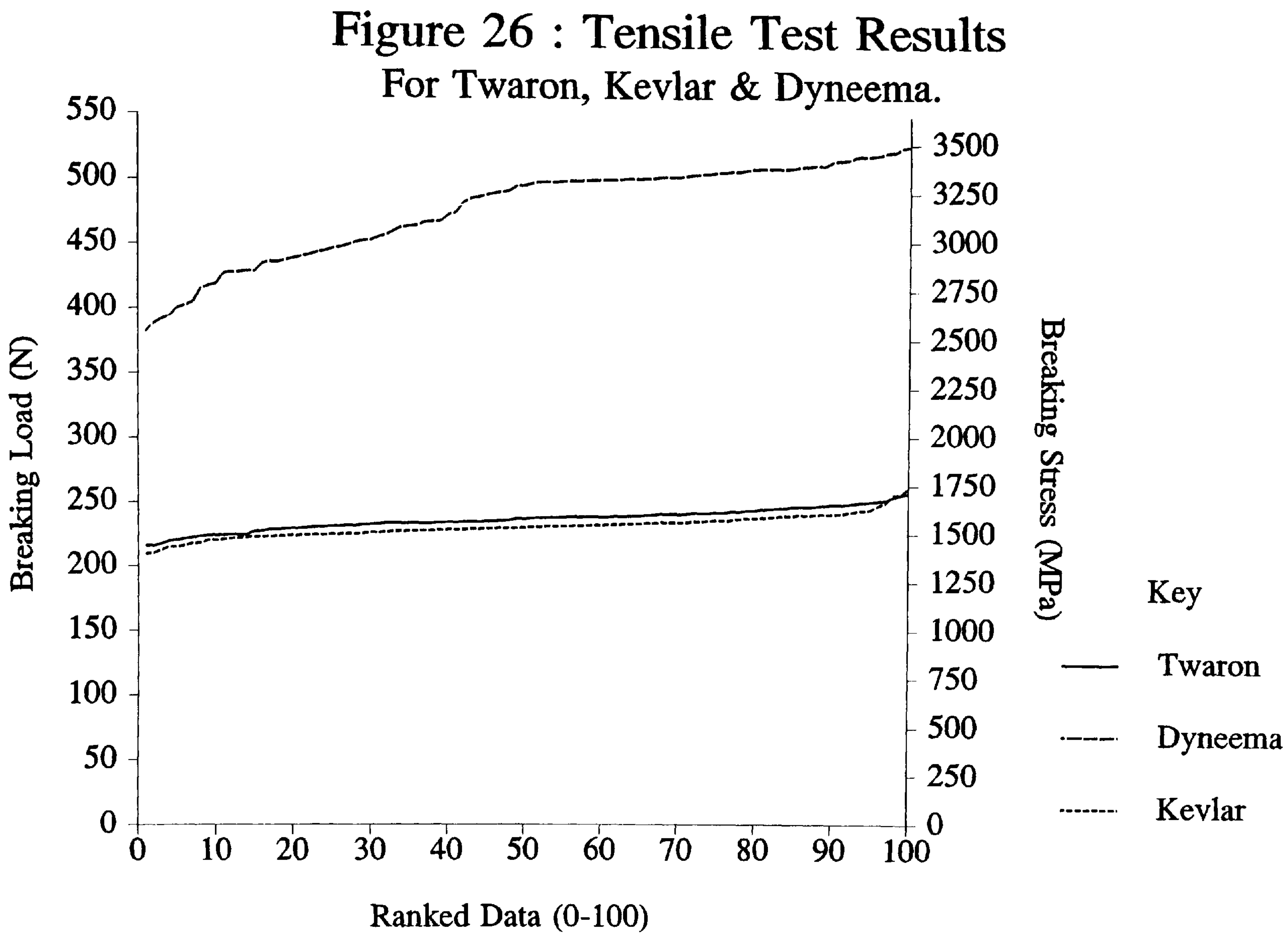


Figure 26 : Tensile Test Results
For Twaron, Kevlar & Dyneema.
Breaking Load (N)
550
500
450
400
350
300
250
200
150
100
50
0
Breaking Stress (MPa)
3500
3250
3000
2750
2500
2250
2000
1750
1500
1250
1000
750
500
250
0
0
10
20
30
40
50
60
70
80
90
100
Ranked Data (0-100)
Key
Twaron
Dyneema
Kevlar

Figure 27 : Distribution of Tensile Test Results
For AKZO Twaron Type 1055 (1610 dtex).

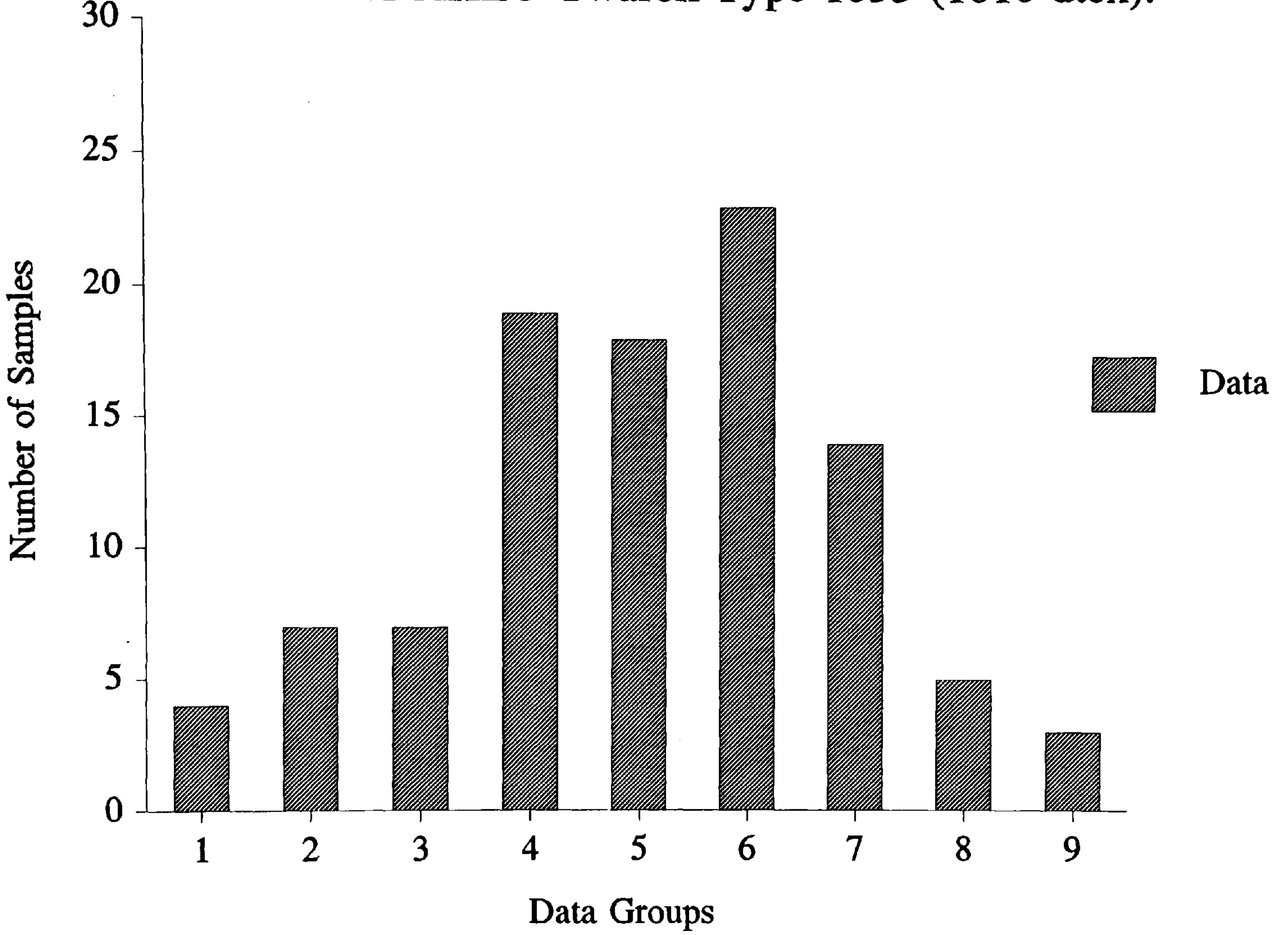


Figure 28 : Distribution of Tensile Test Results
For DuPont Kevlar 49 (1580 dtex).

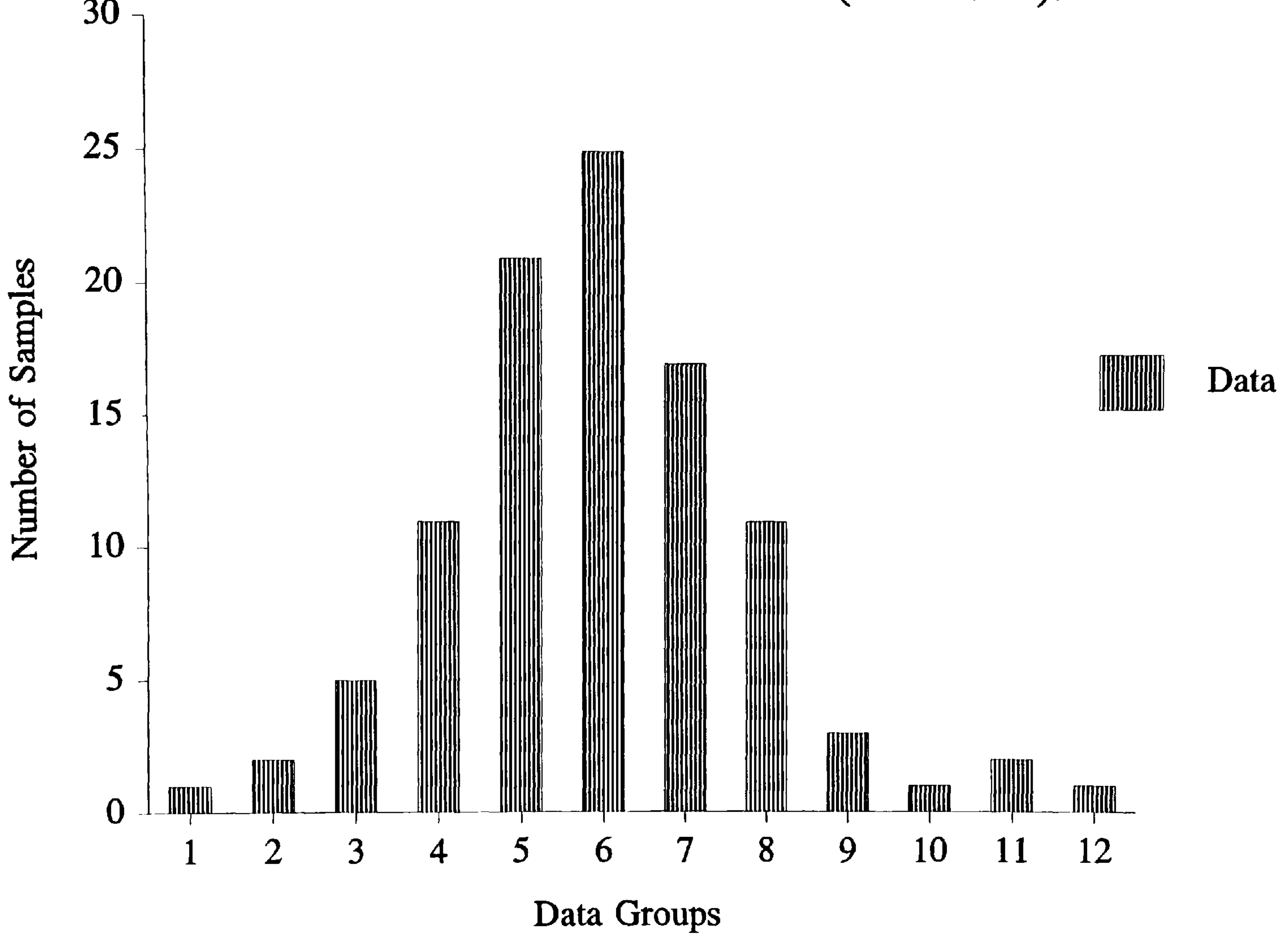


Figure 29 : Distribution of Tensile Test Results
For DSM Dyneema SK65 (1760 dtex).

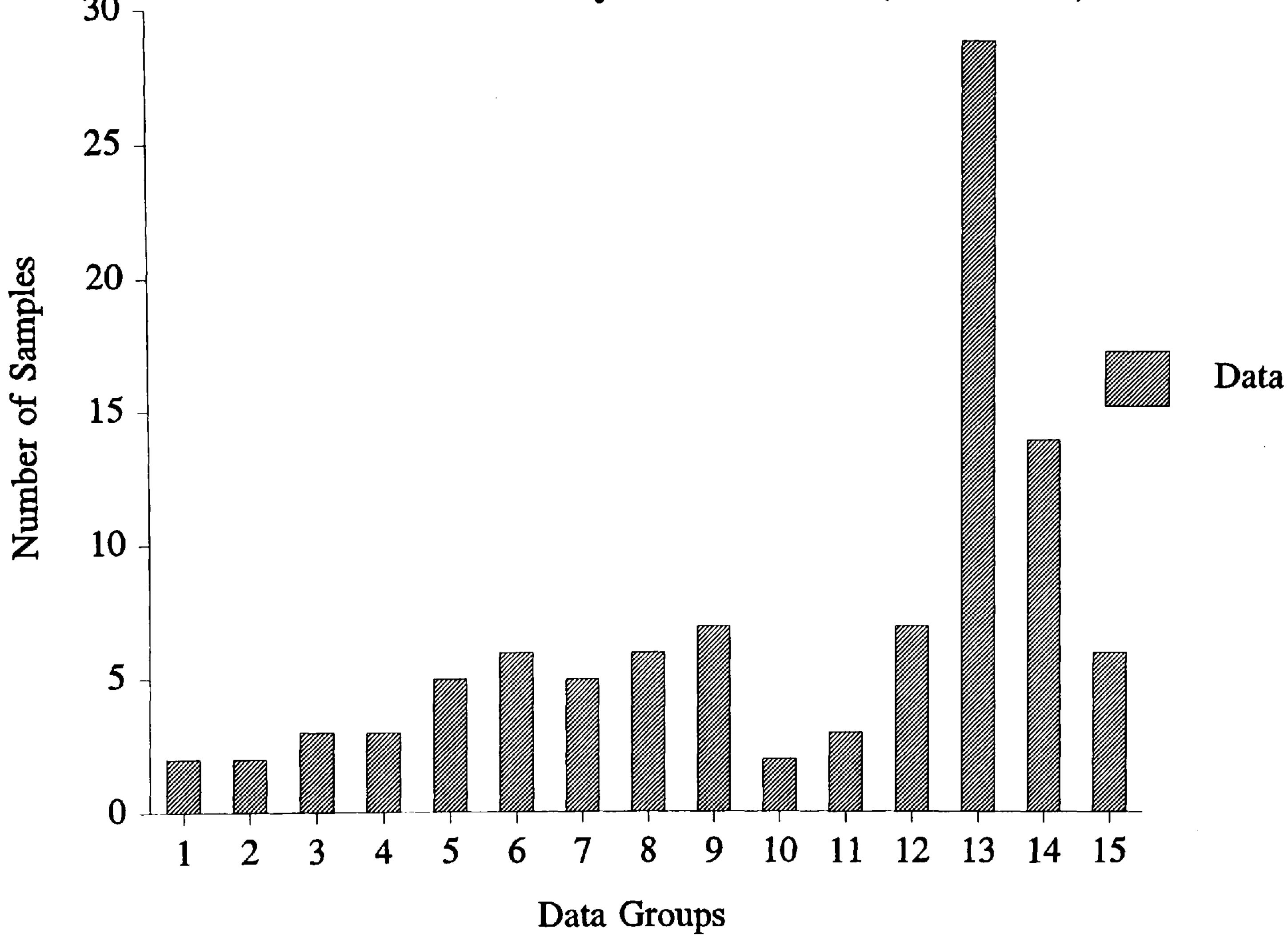


Figure 30 : Distribution of Tensile Test Results
For Twaron & Kevlar.

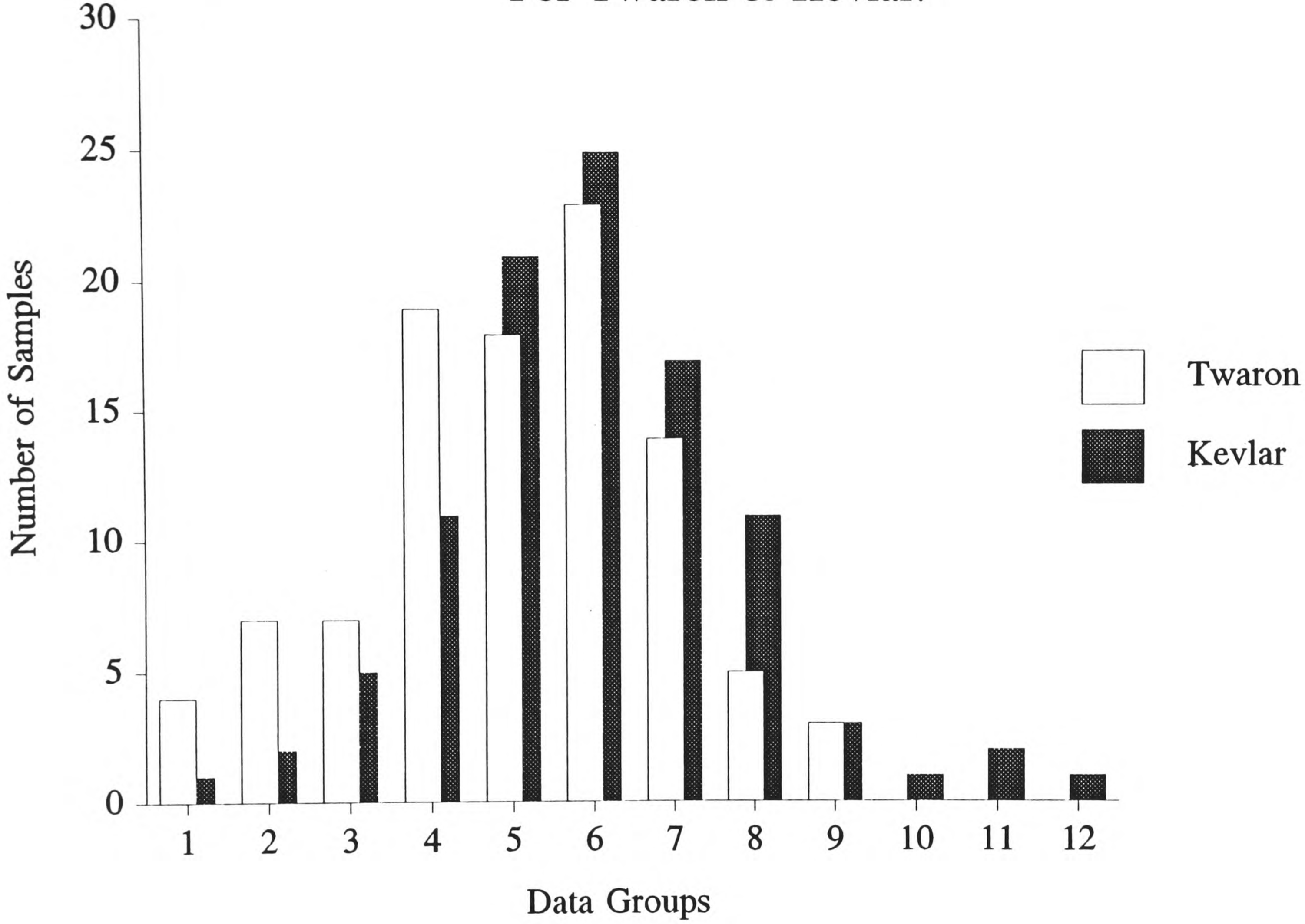


Figure 31 : Weibull Plot for Akzo Twaron (1610 dtex)

Weibull Shape Parameter = 30.9

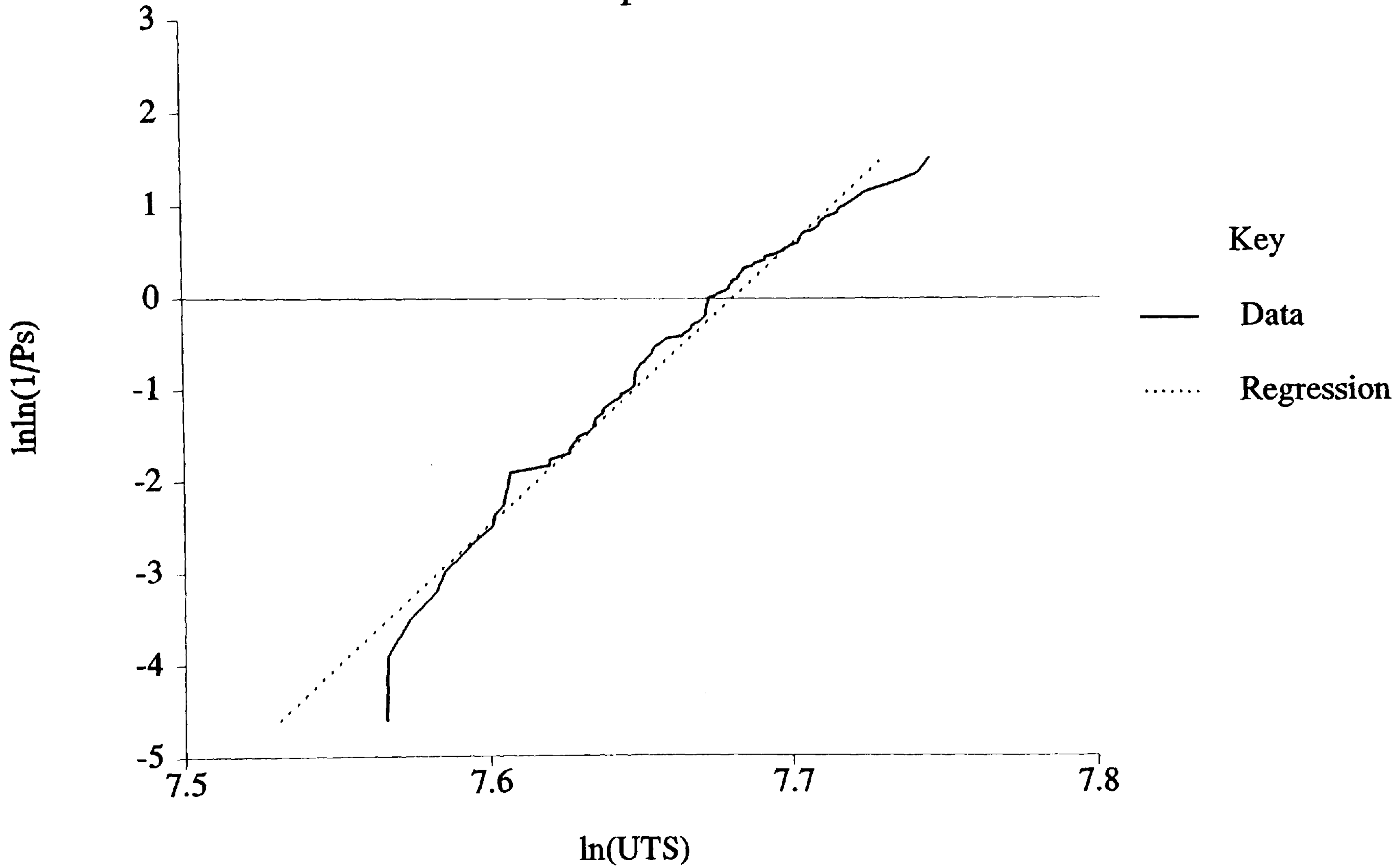


Figure 32 : Weibull Plot for DuPont Kevlar 49 (1580 dtex)

Weibull Shape Parameter = 29.0

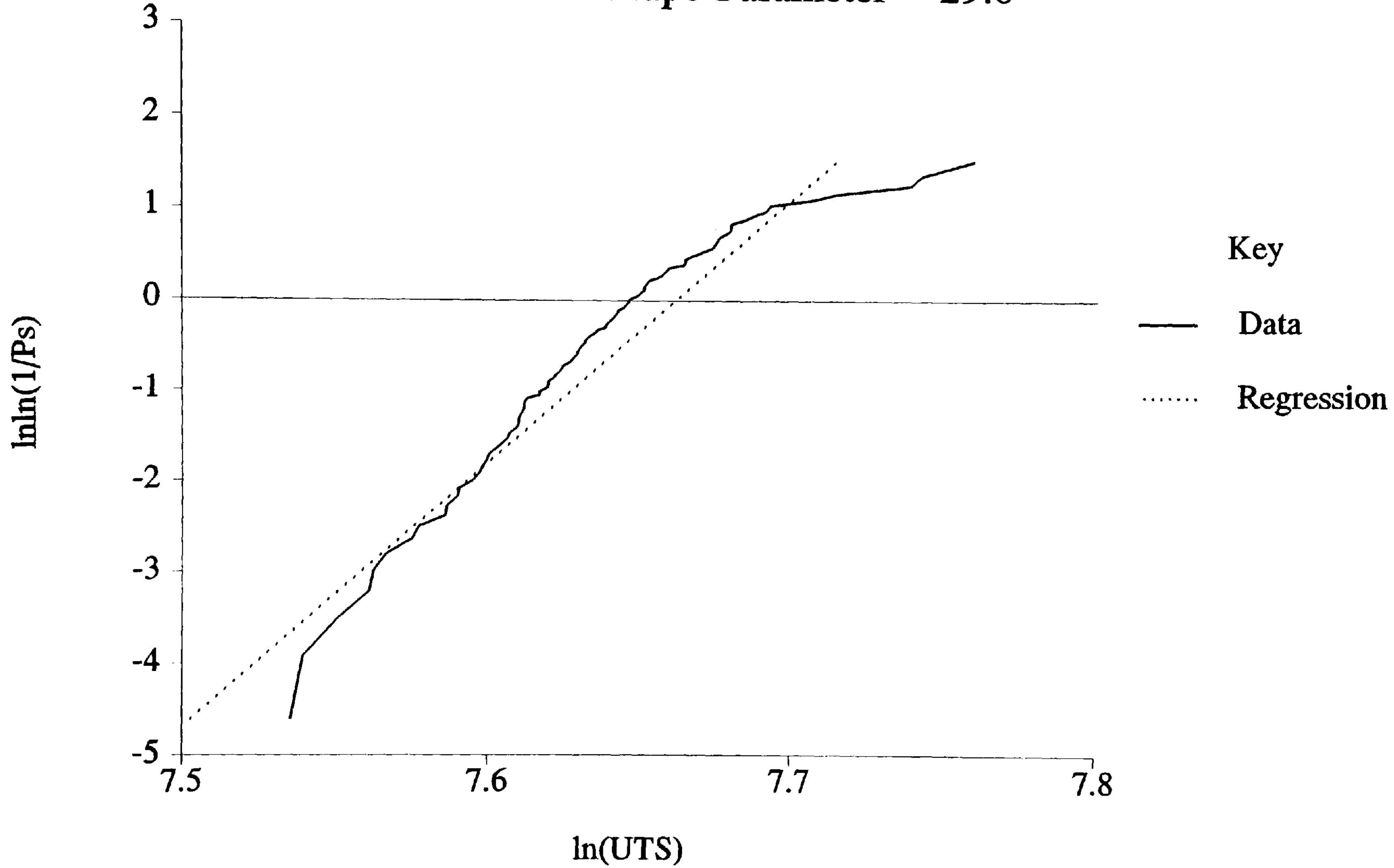


Figure 33 : Weibull Plot for DSM Dyneema SK65 (1760 dtex)

Weibull Shape Parameter = 12.2

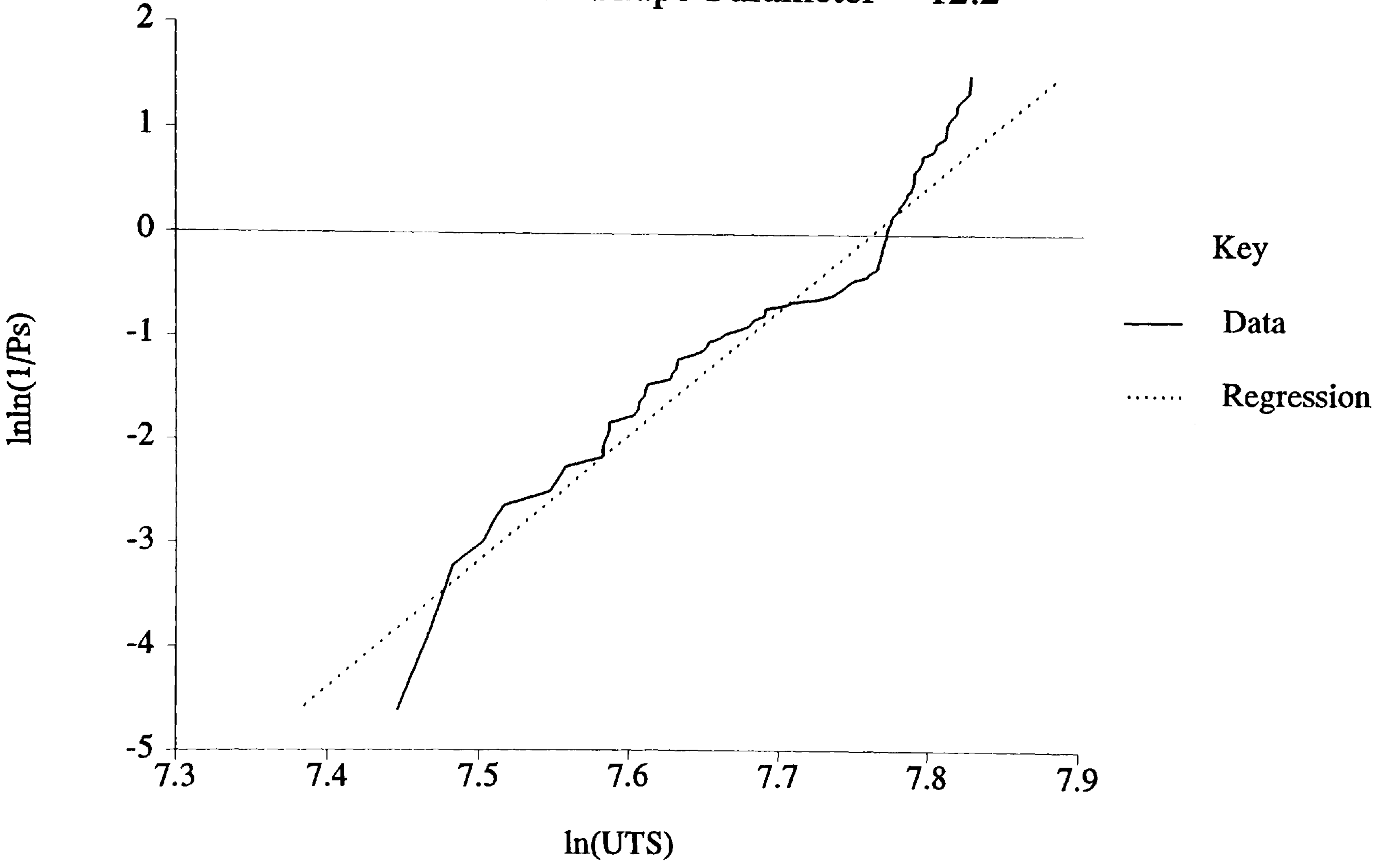


Figure 34 : Probability of Tensile Failure Plot
For Twaron, Kevlar & Dyneema.

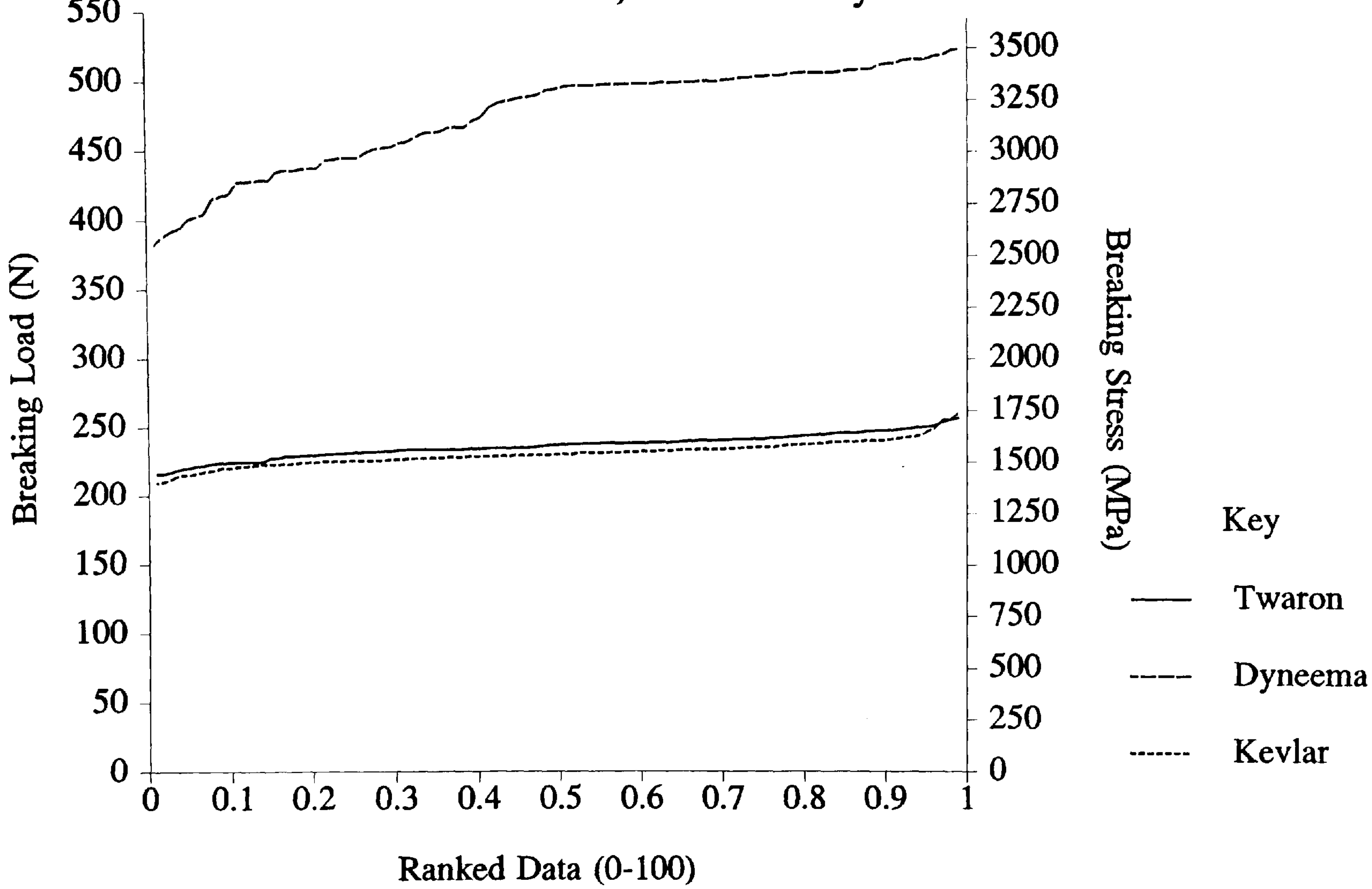


Figure 35 : LASE Test Results
For Material Yarn Types.

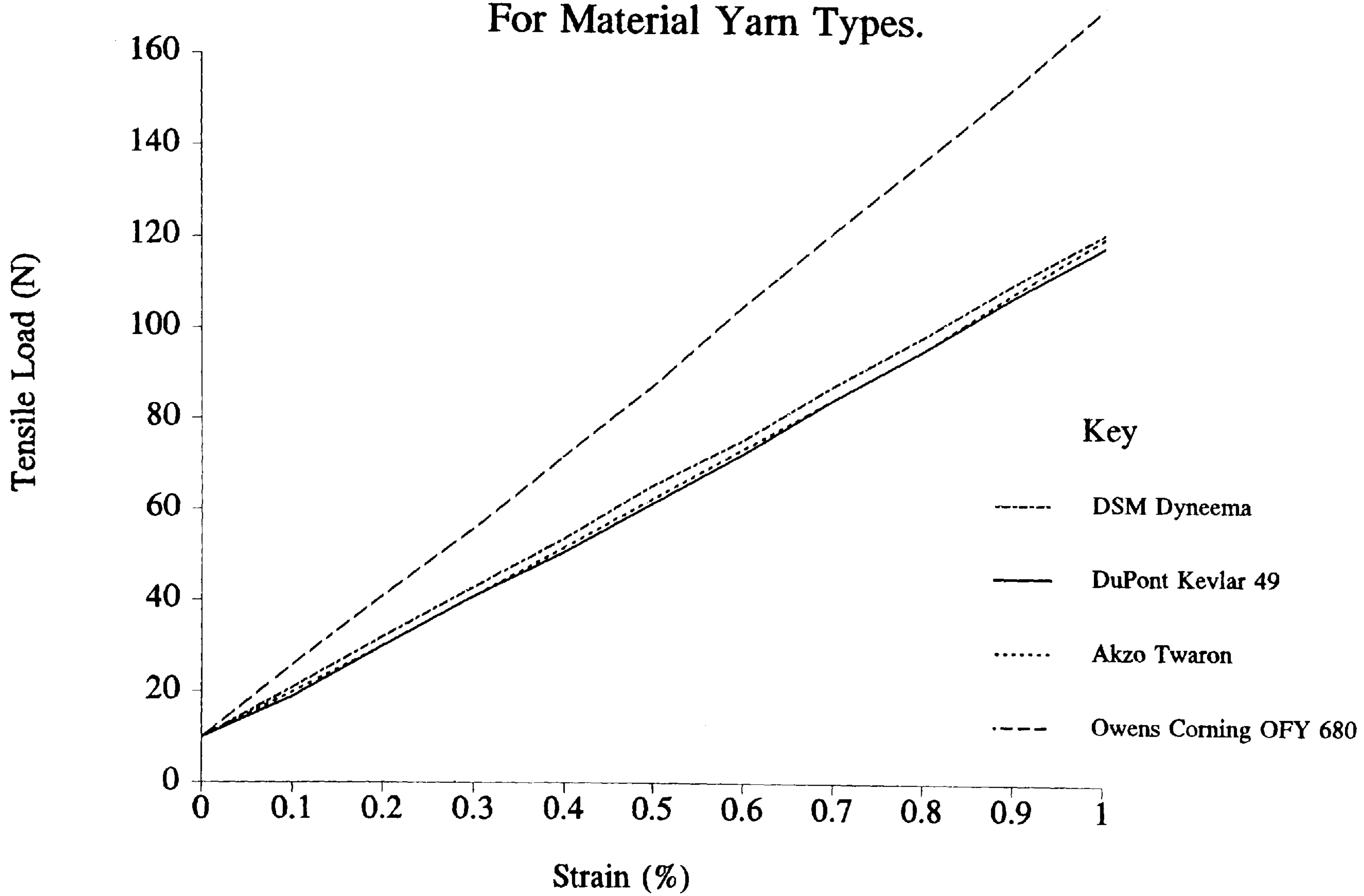


Figure 36 : LASE Test Results
For Material Yarn Types.

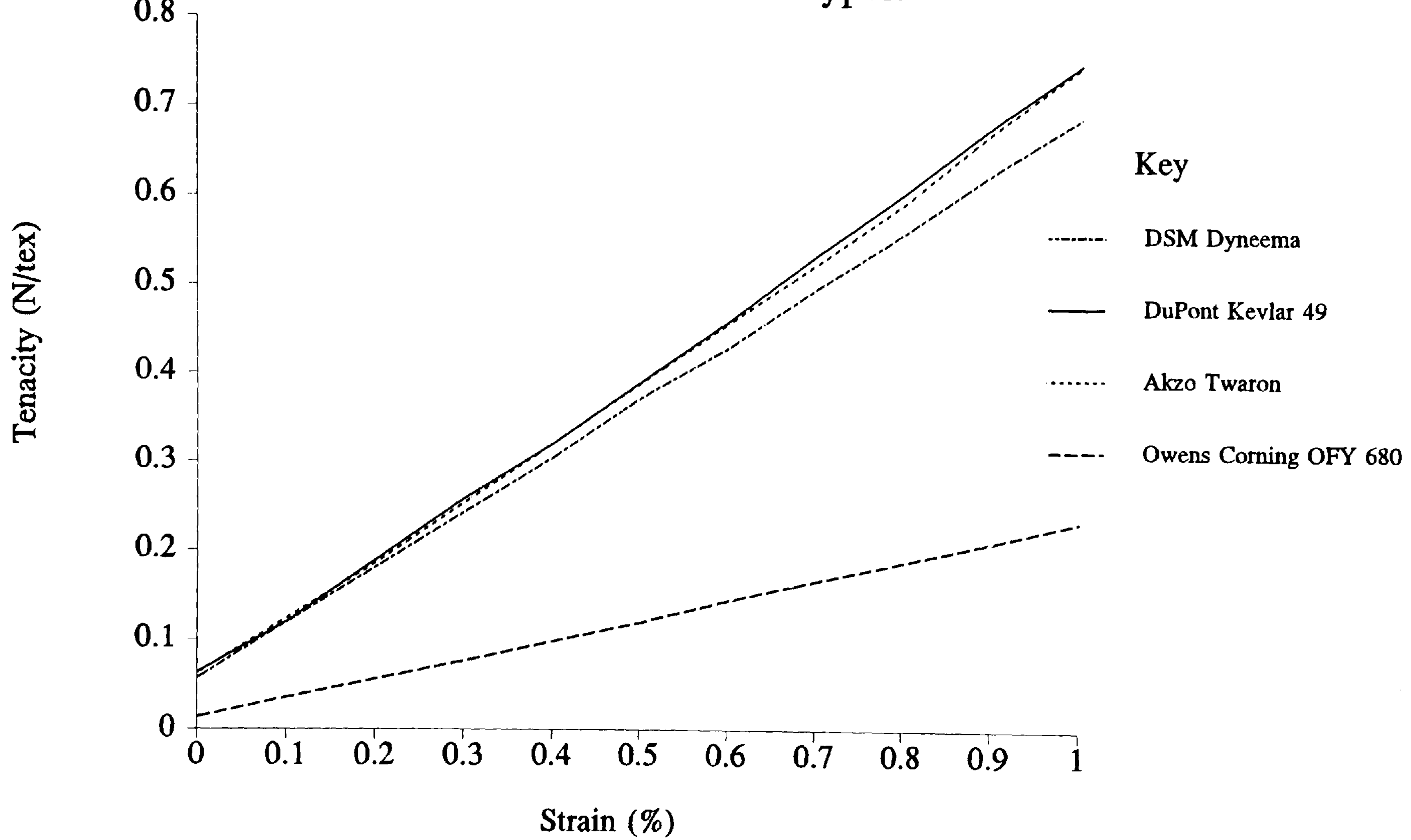


Figure 37 : Cable IDS LASE Test Results
For (22x8050) Aramid + 2mm GRP Rod Cable

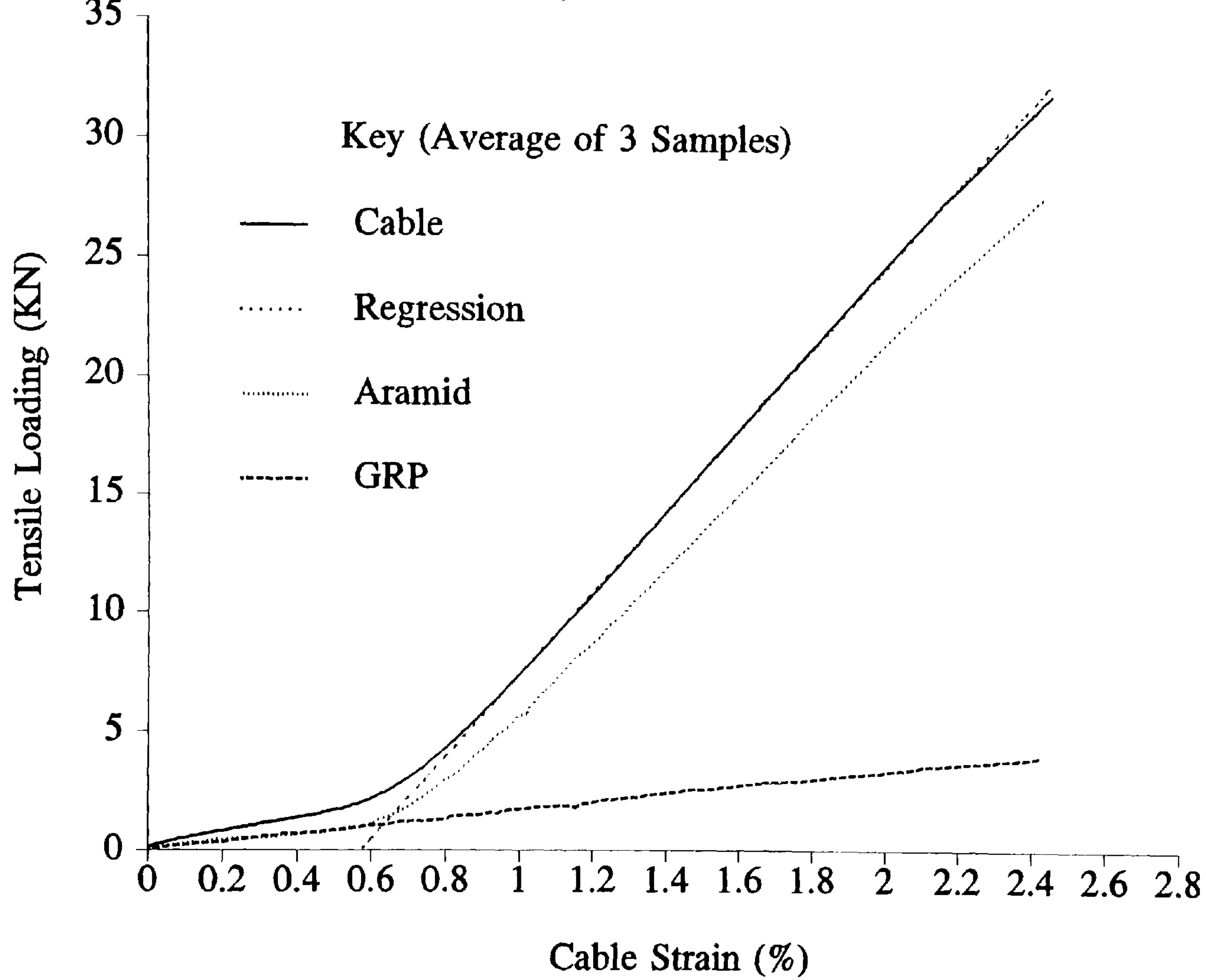


Figure 38 : Yarn Creep Test Results
Yarn Creep Only

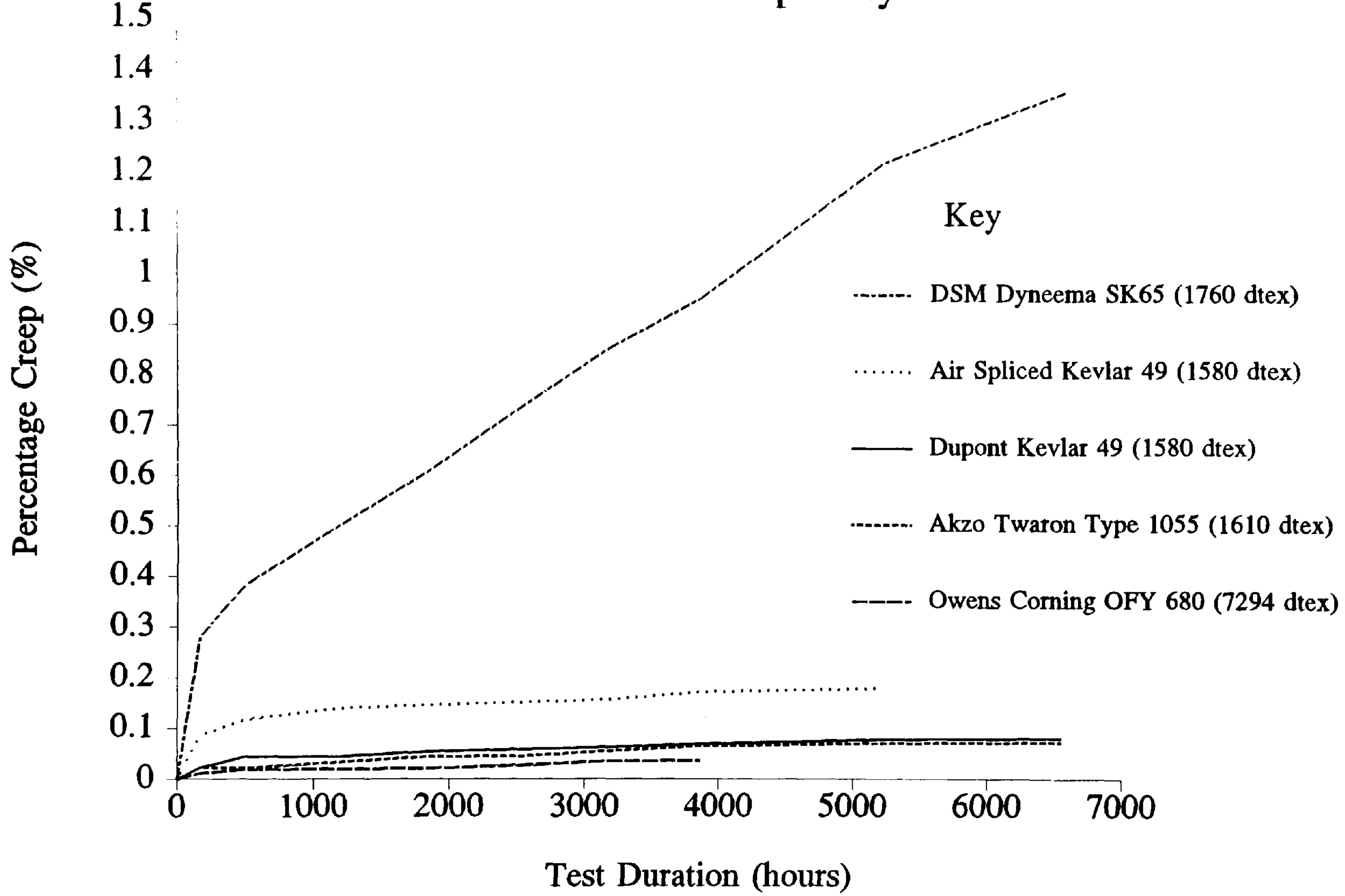


Figure 39 : Log Yarn Creep Test Results

Yarn Creep Only

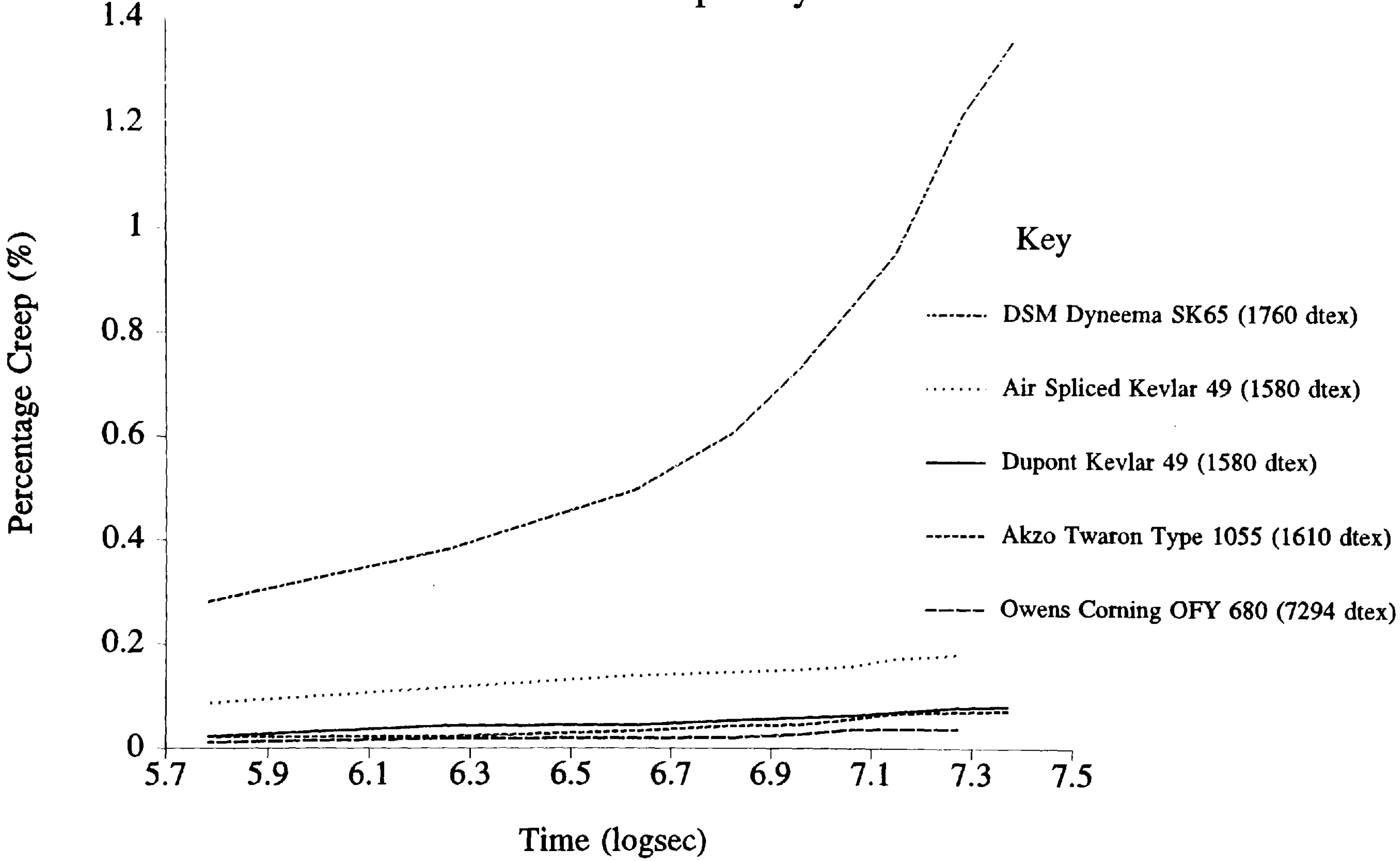


Figure 40 : Yarn Creep Test Results

Total Yarn Elongation

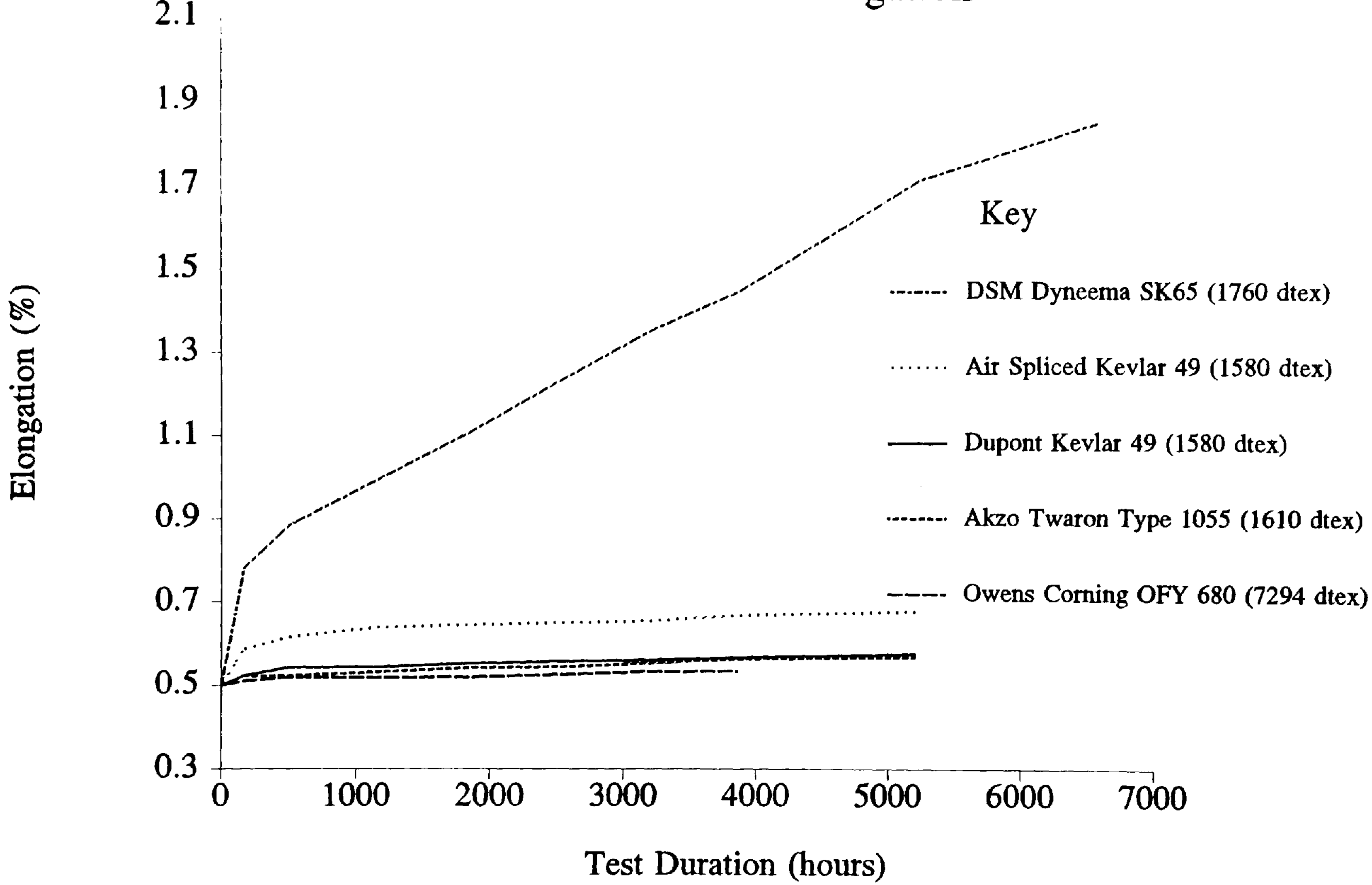


Figure 41 : Log Yarn Creep Test Results

Total Yarn Elongation

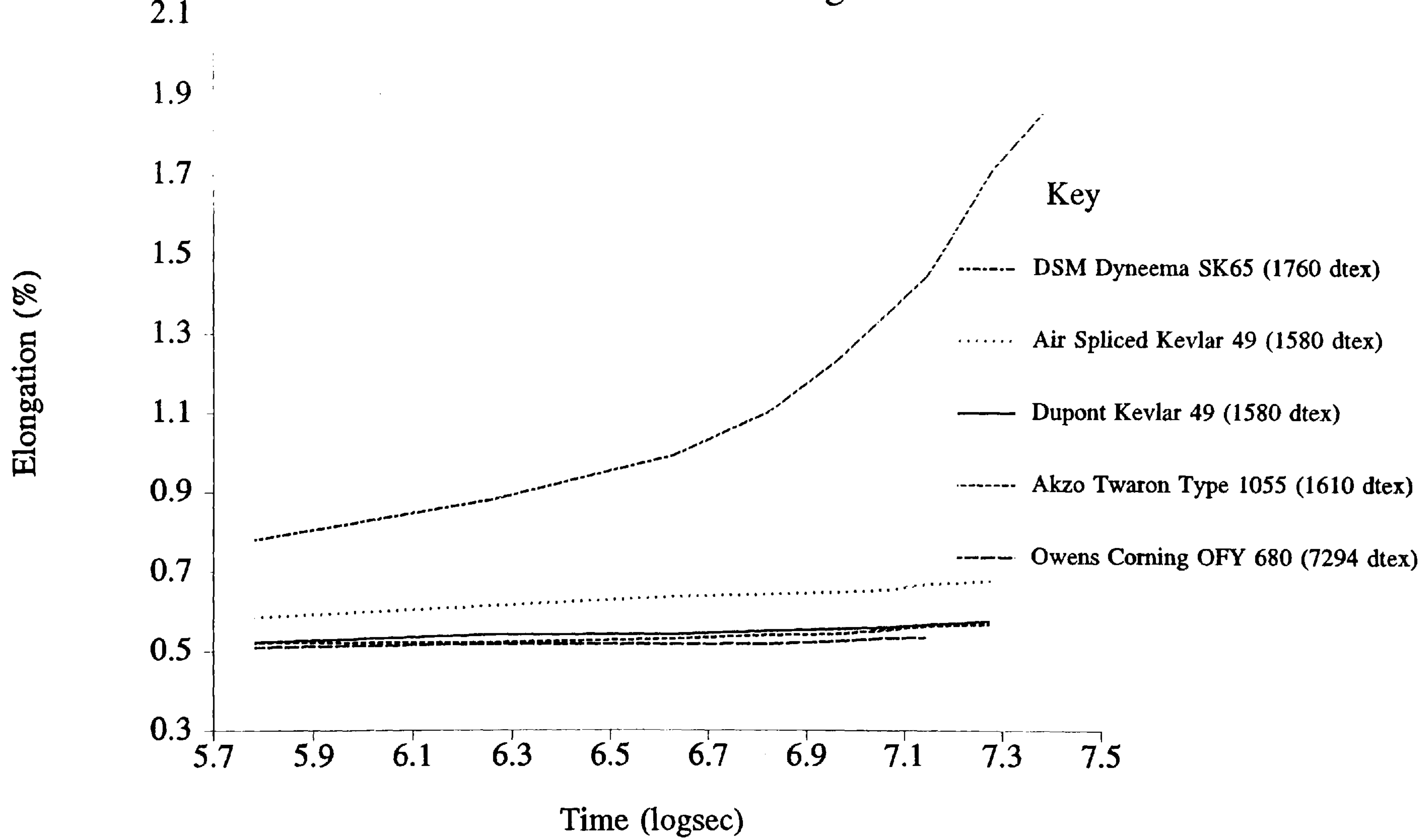


Figure 42 : Cable Creep Test Results

Creep Loading 8.8 KN

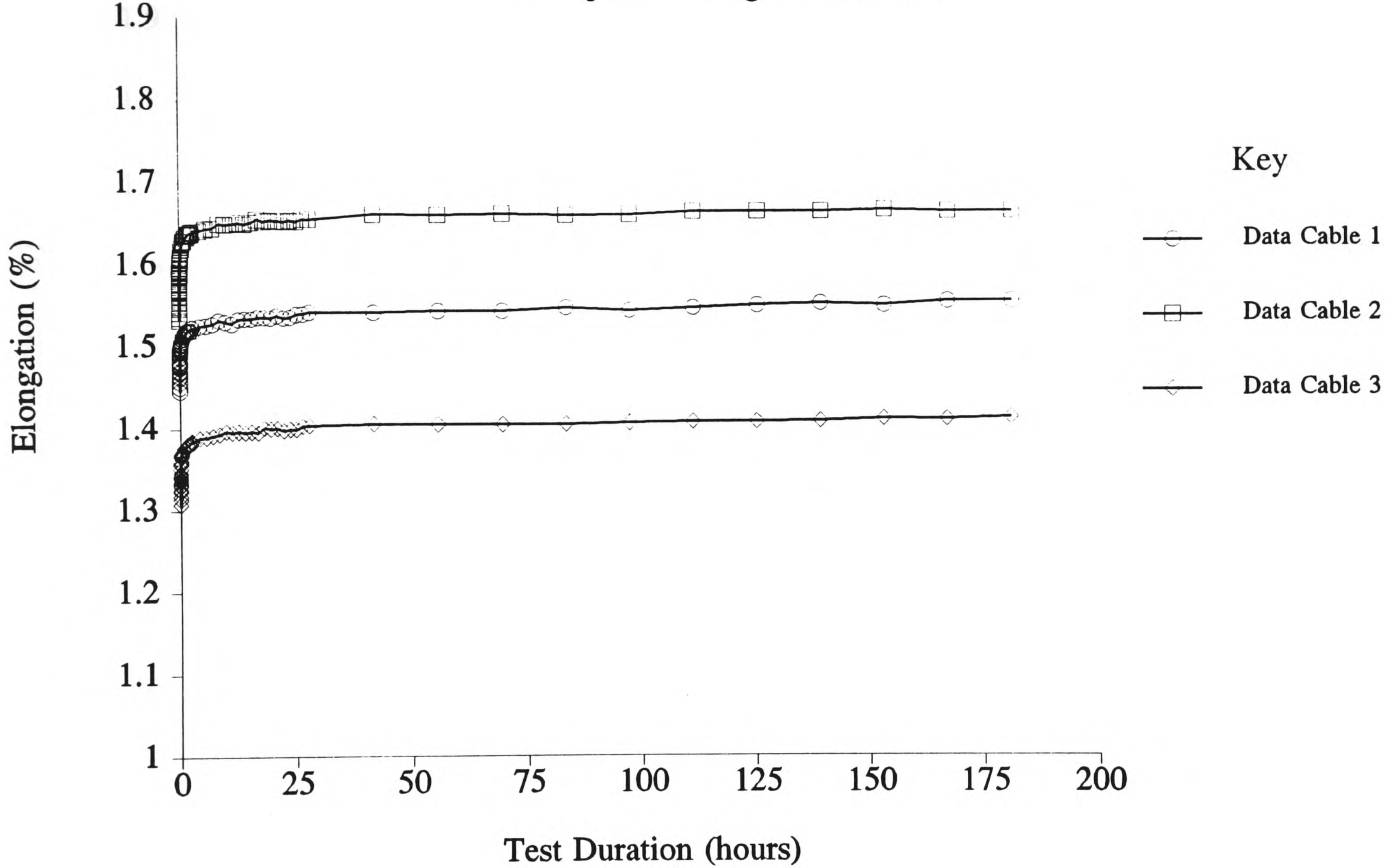


Figure 43 : Log Cable Creep Test Results

Creep Loading 8.8 KN

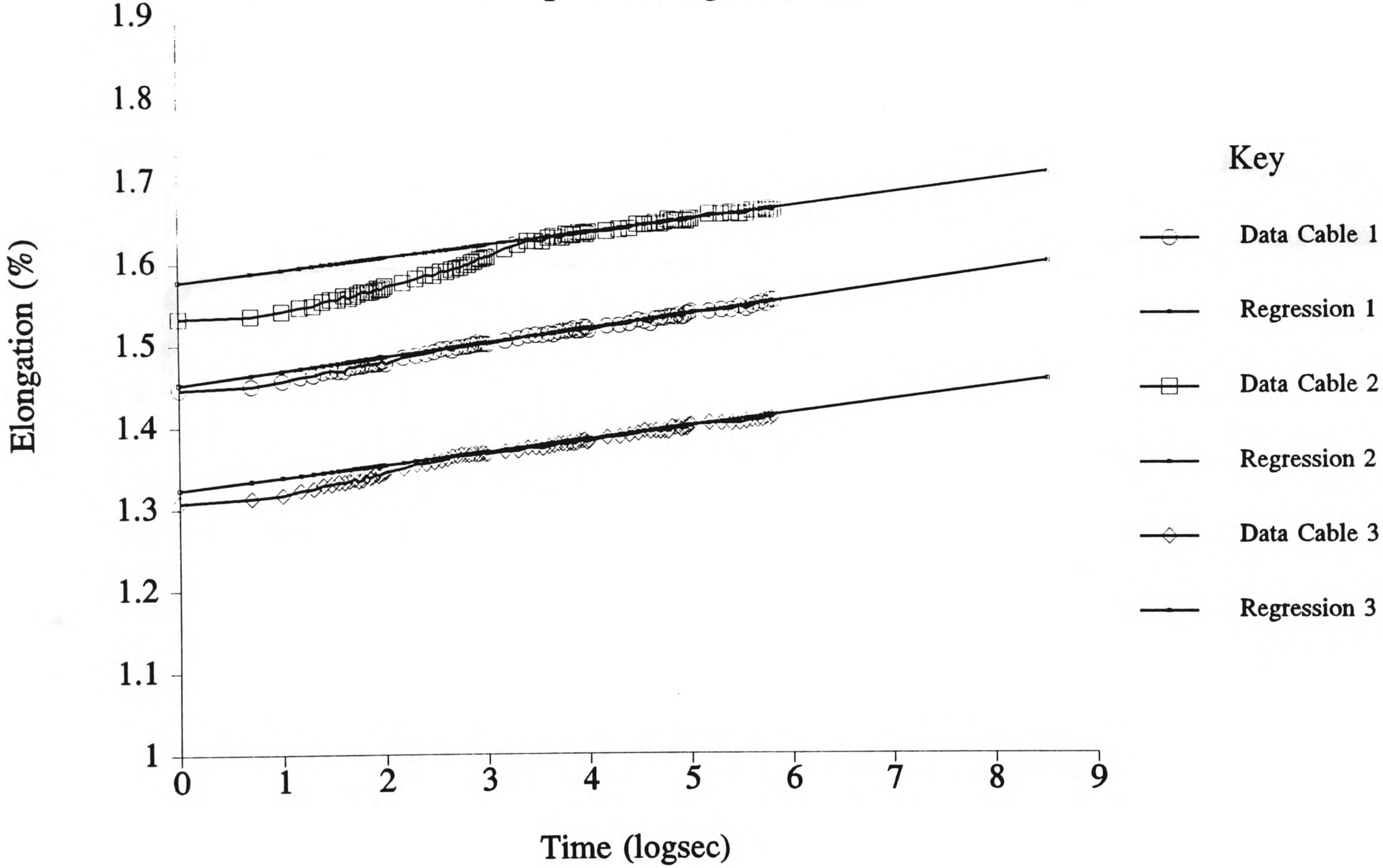


Figure 44 : Average Cable Creep Test Results
Creep Loading 8.8 KN

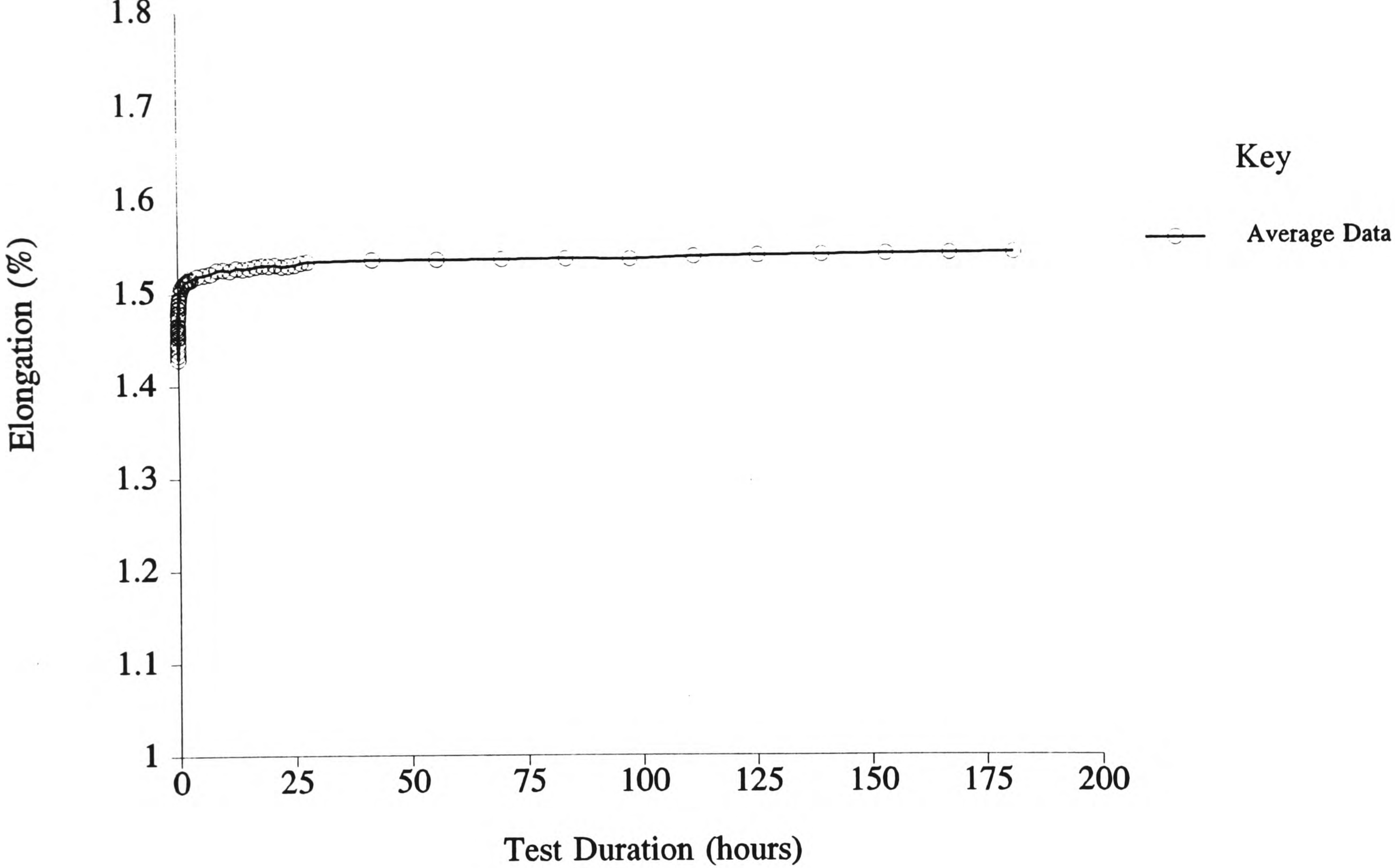


Figure 45 : Log Average Cable Creep Test Results

Creep Loading 8.8 KN

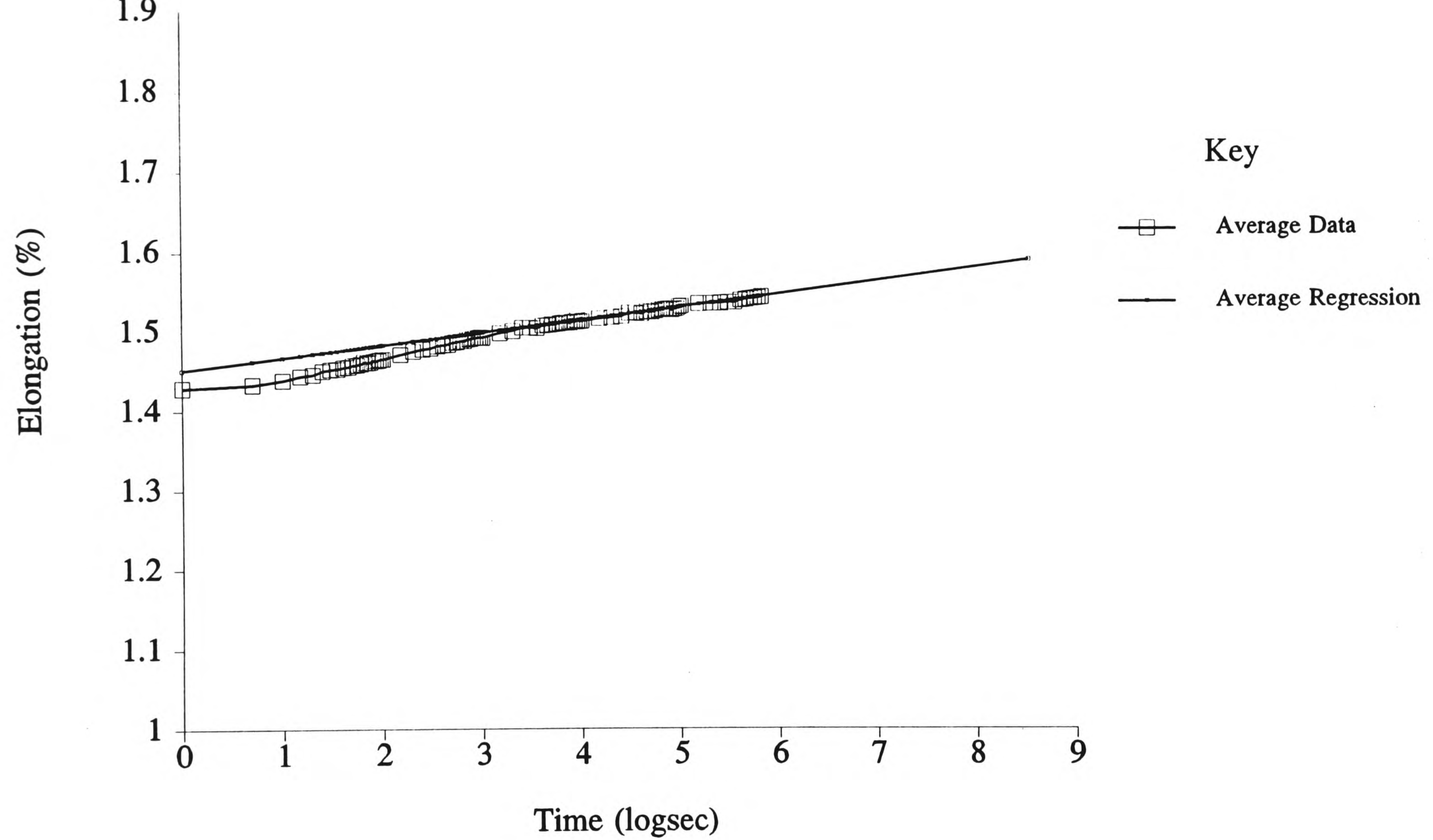


Figure 46 : Fatigue Test Results
For Aramid Materials

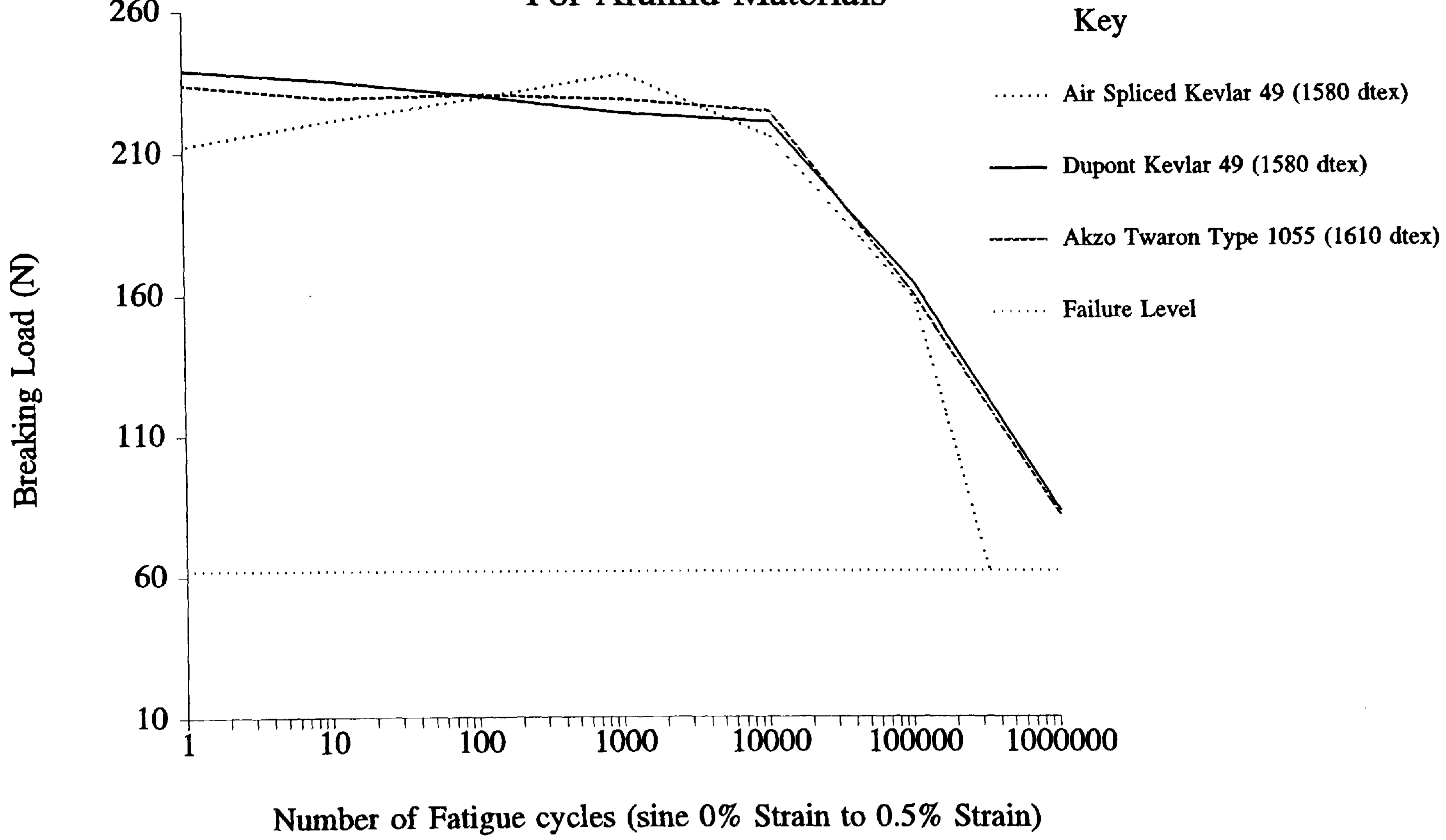


Figure 47 : Fatigue Test Results
For Yarn Materials

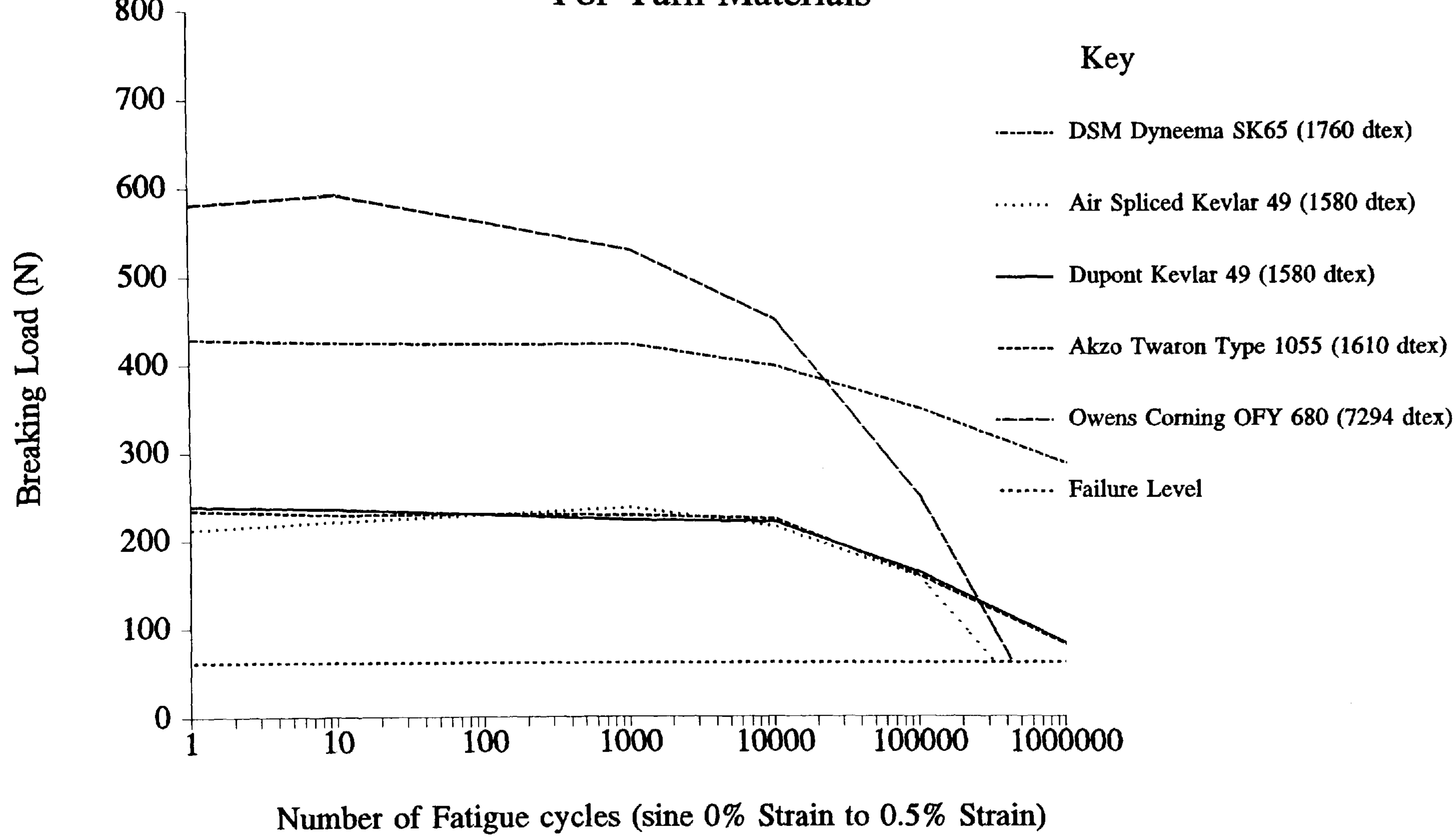


Figure 48 : Jointed Kevlar 49 Yarn Creep Test Results

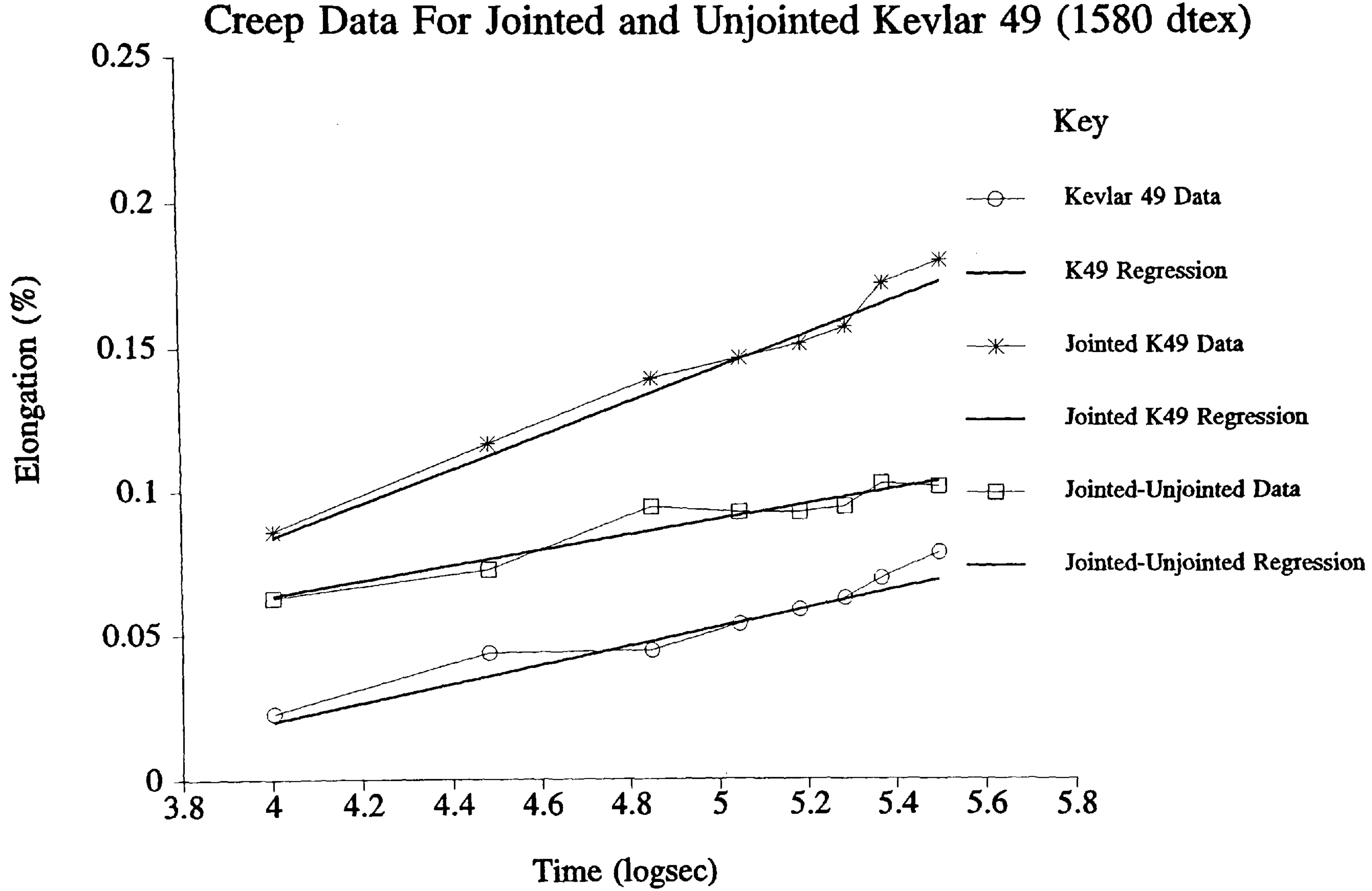


Figure 49 : Creep Performance of Jointed Aramid Yarn

Comparison of Jointed Kevlar 49 with Unjointed Kevlar 49

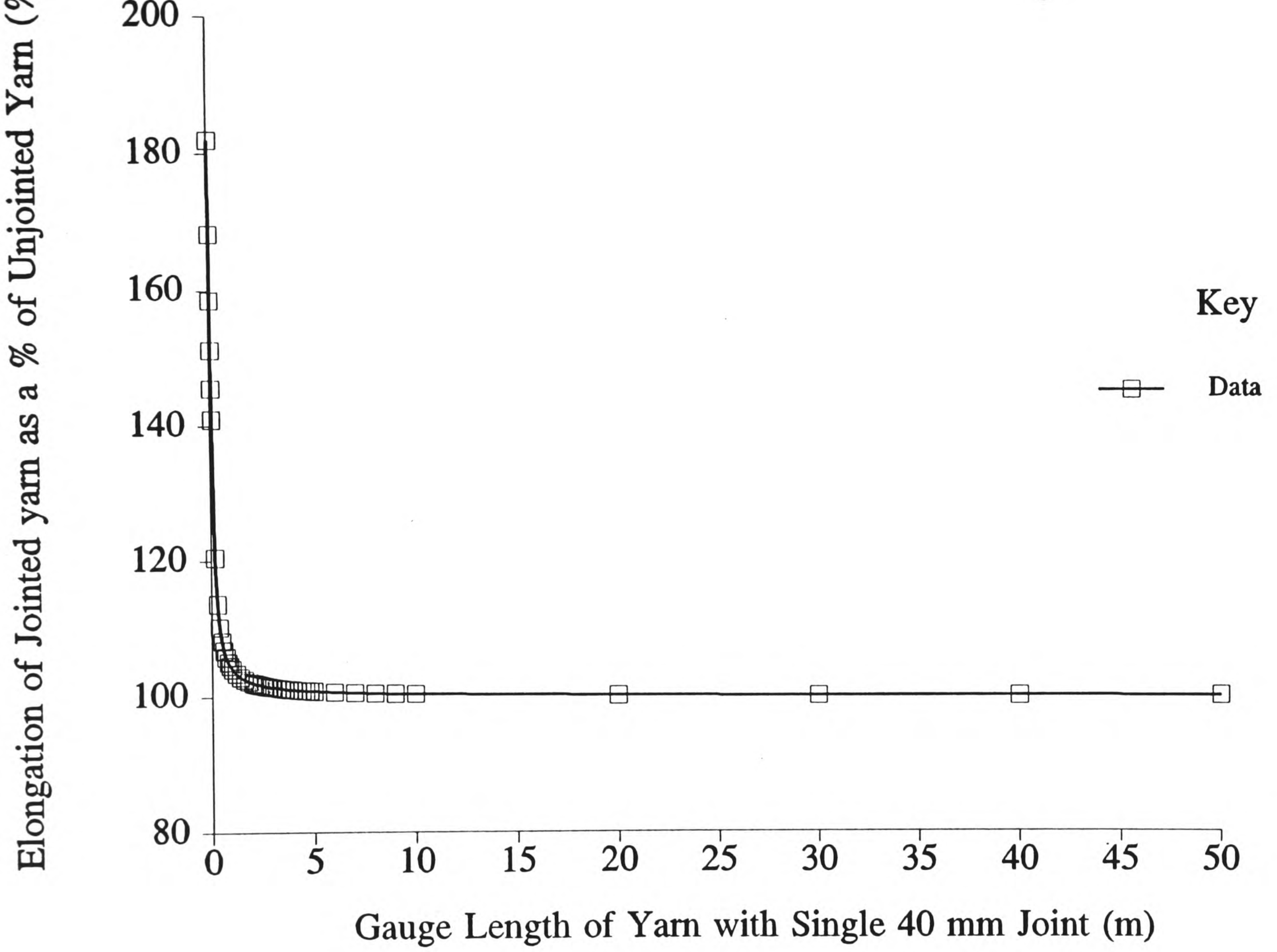


Figure 50 : Creep Performance of Jointed Aramid Yarn
Comparison of Jointed Kevlar 49 with Unjointed Kevlar 49

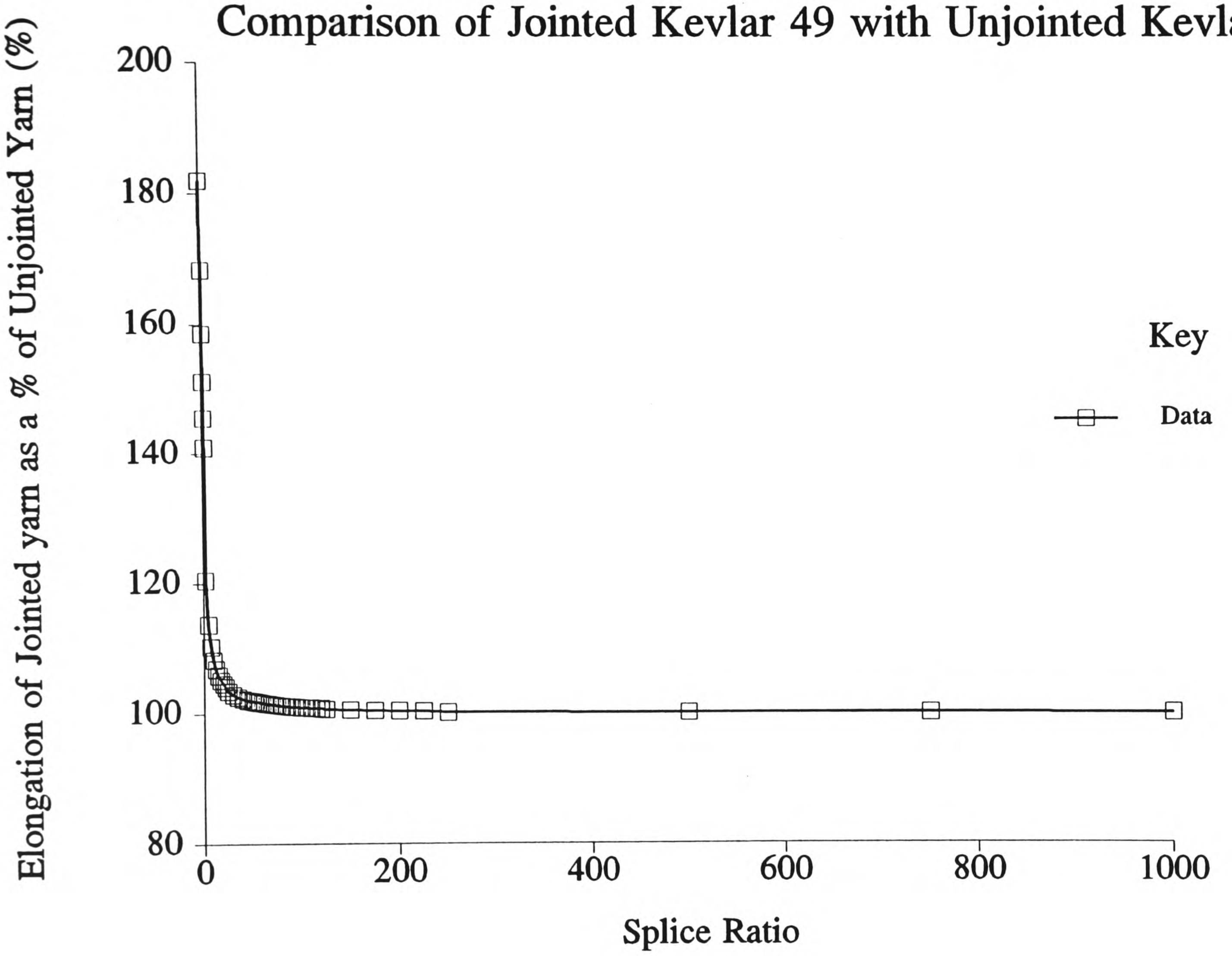


Figure 51 : Aramid & Jointed Aramid LASE Test Results

For Jointed Kevlar 49 (1580 dtex), 40 mm G.L., 40 mm Splice

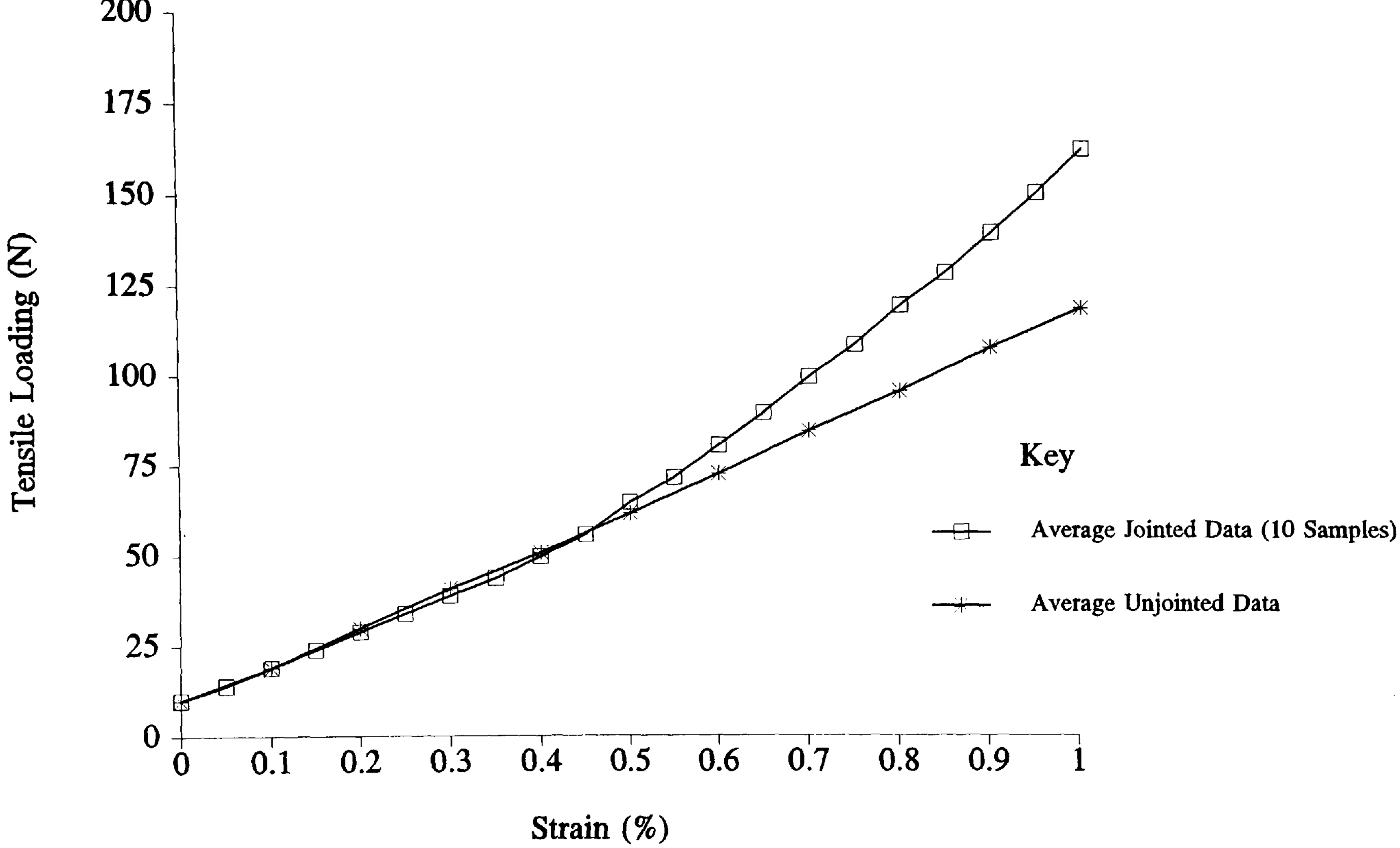


Figure 52 : LASE Performance of Jointed Aramid Yarn

Comparison of Jointed Kevlar 49 with Unjointed Kevlar 49

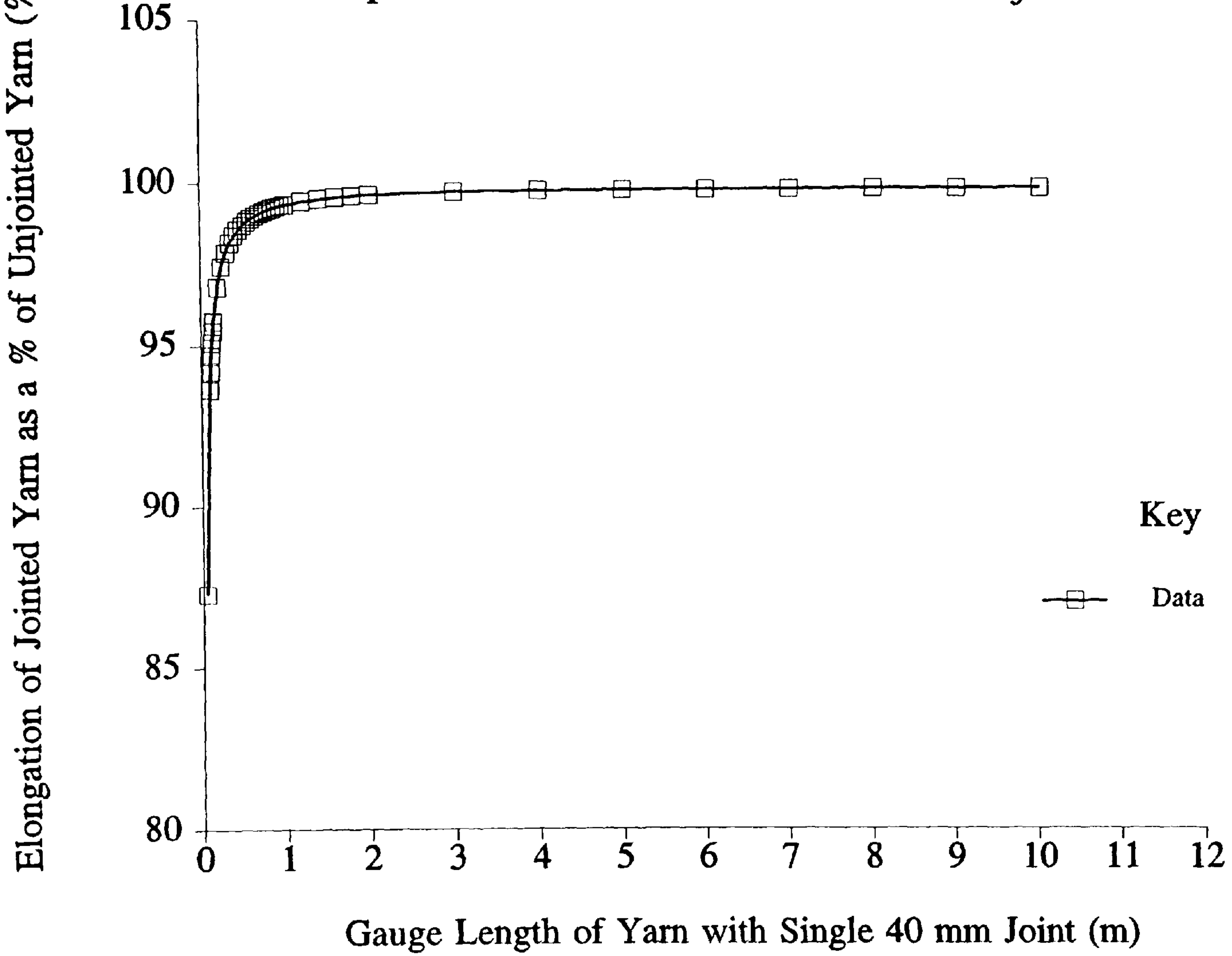


Figure 53 : LASE Performance of Jointed Aramid Yarn

Comparison of Jointed Kevlar 49 with Unjointed Kevlar 49

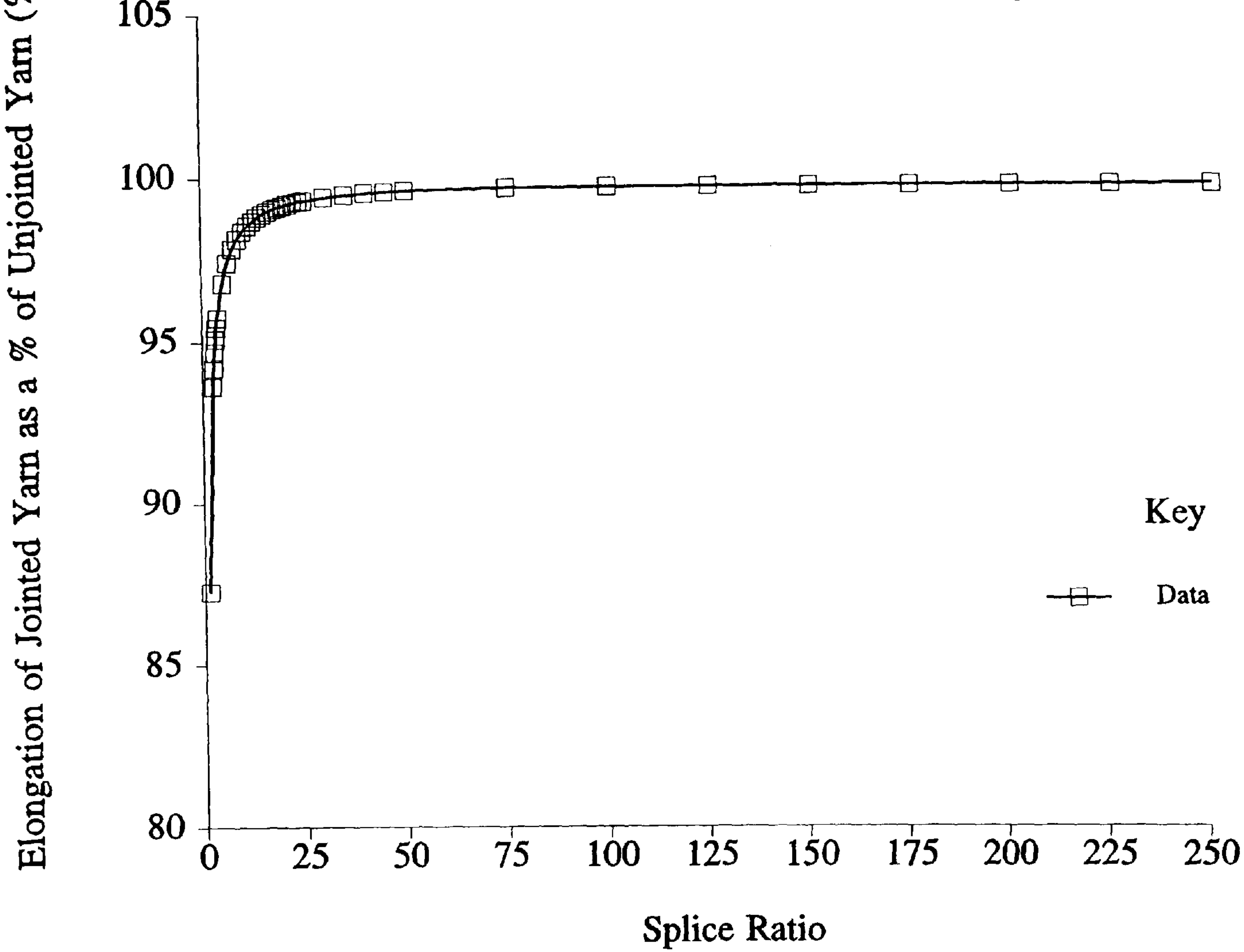


Figure 54 : Hydrochloric Acid Ageing Test Tensile Results

For Samples Aged in 1m HCl

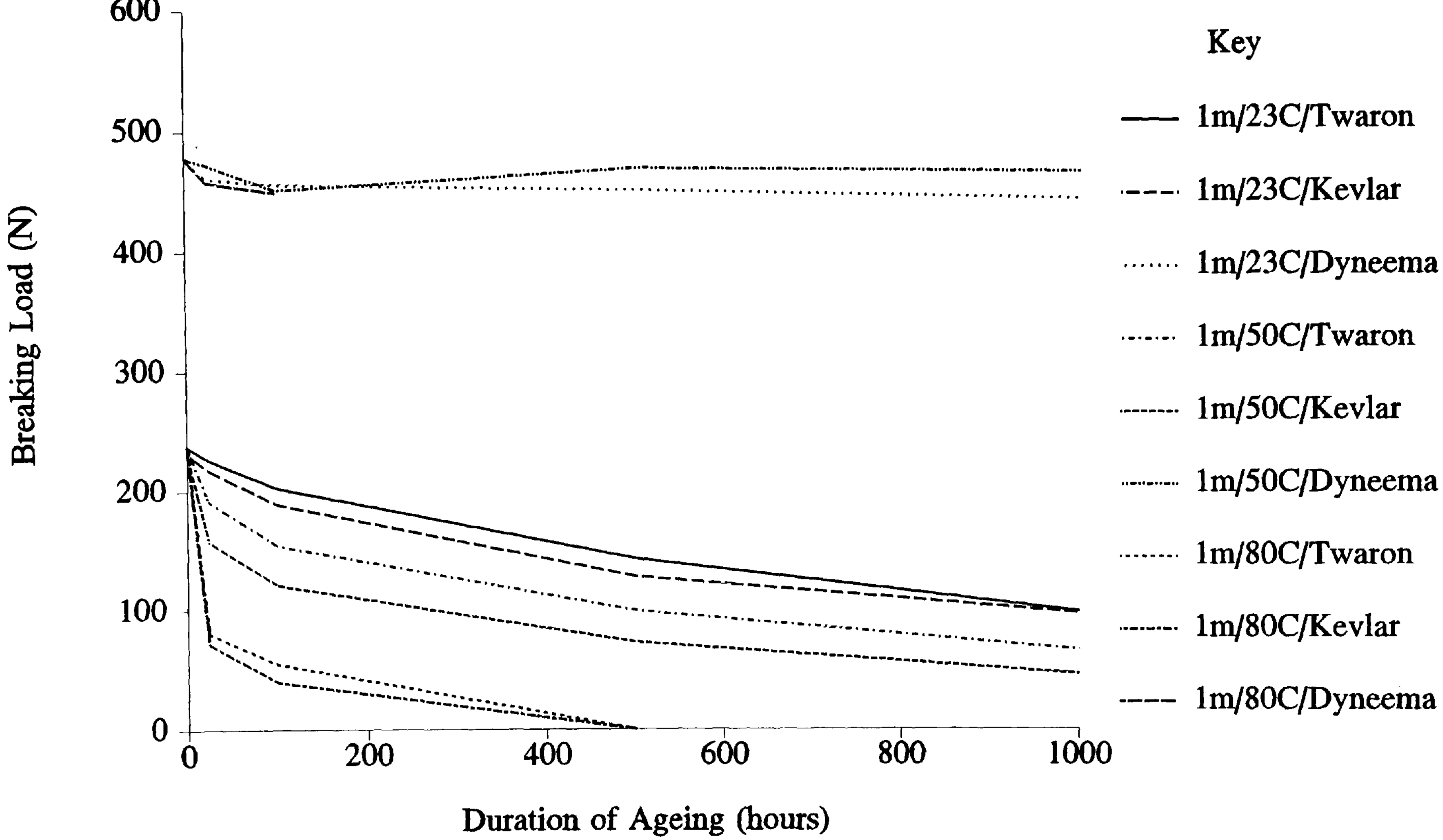


Figure 55 : Hydrochloric Acid Ageing Test Tensile Results
For Samples Aged at 23C

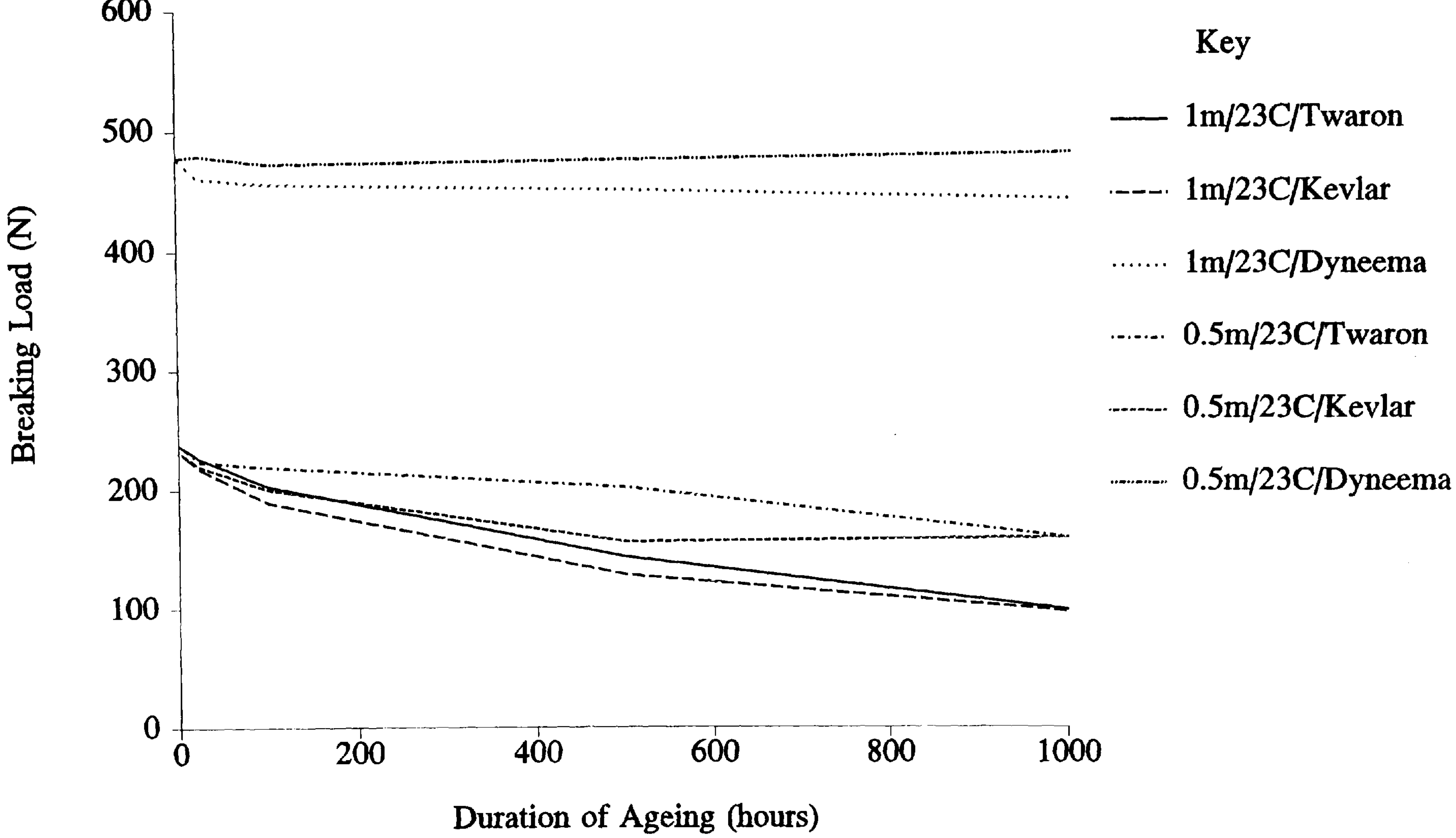


Figure 56 : Sodium Hydroxide Ageing Test Tensile Results

For Samples Aged in 1m NaOH

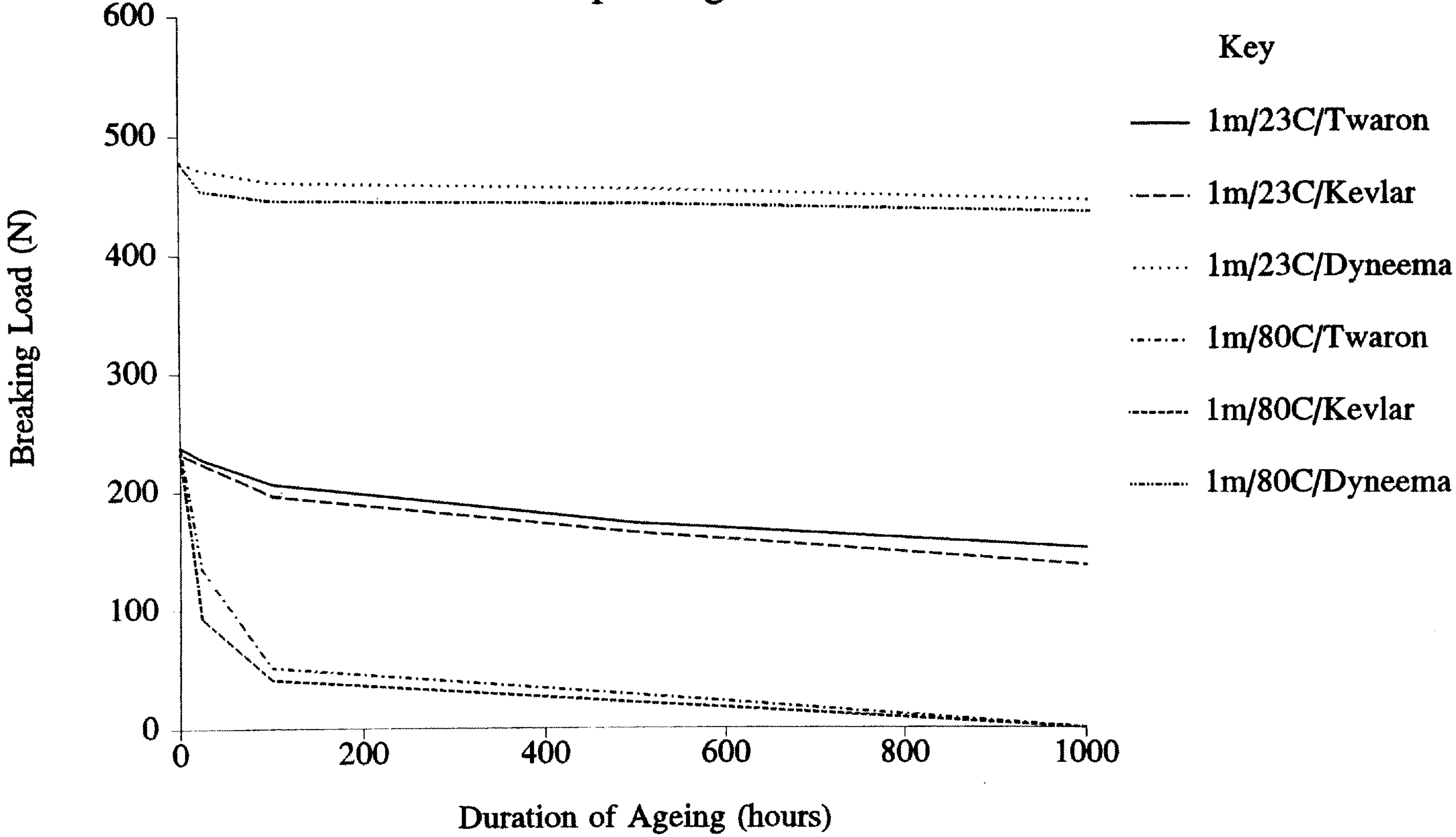


Figure 57 : Detergent Ageing Test Tensile Results

For Samples Aged in 1% Antarox CO-630 Solution

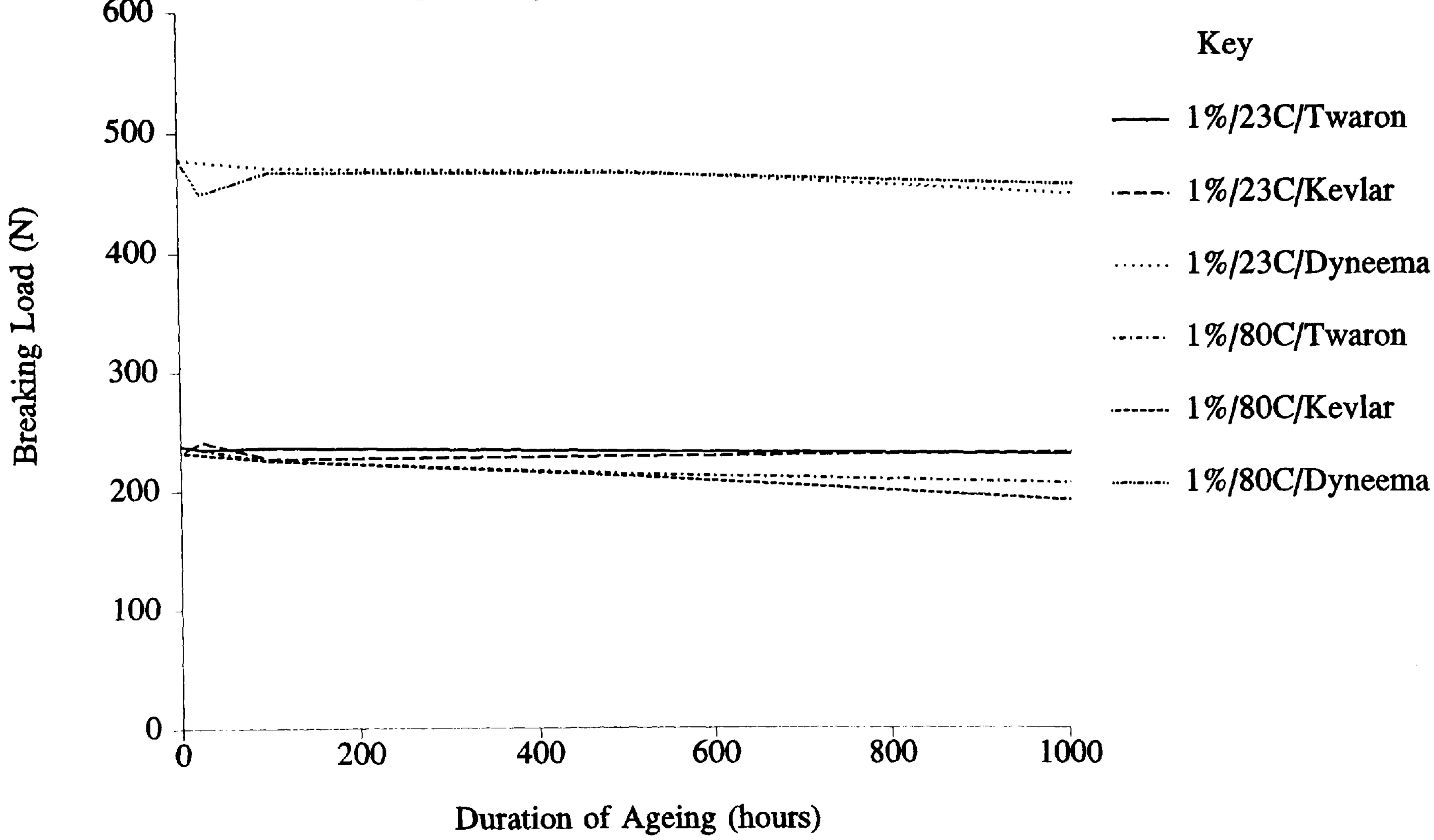


Figure 58 : Diesel Ageing Test Tensile Results
For Samples Aged in DERV Diesel Oil

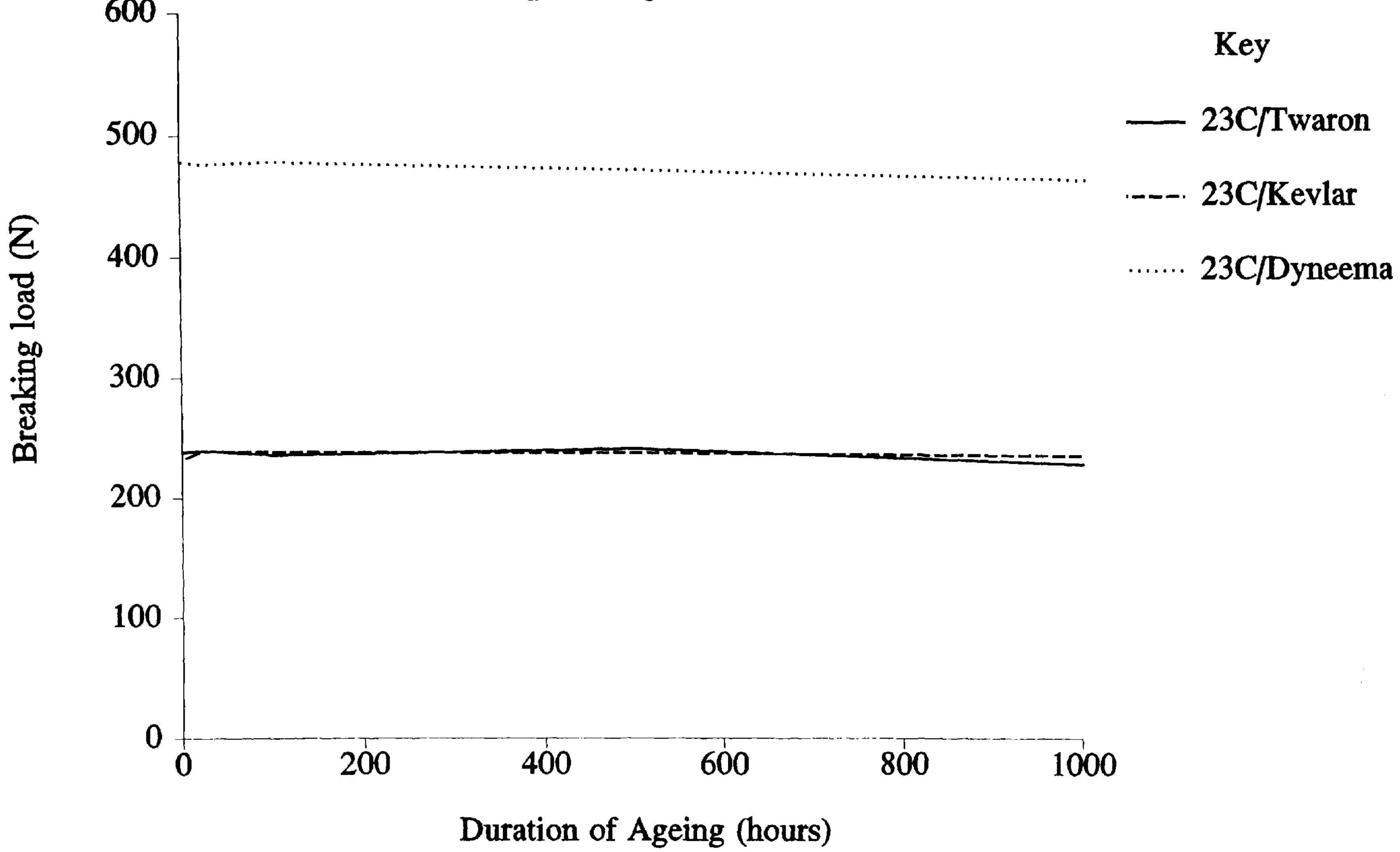


Figure 59 : Petrol Ageing Test Tensile Results
For Samples Aged in Premium Unleaded Petrol

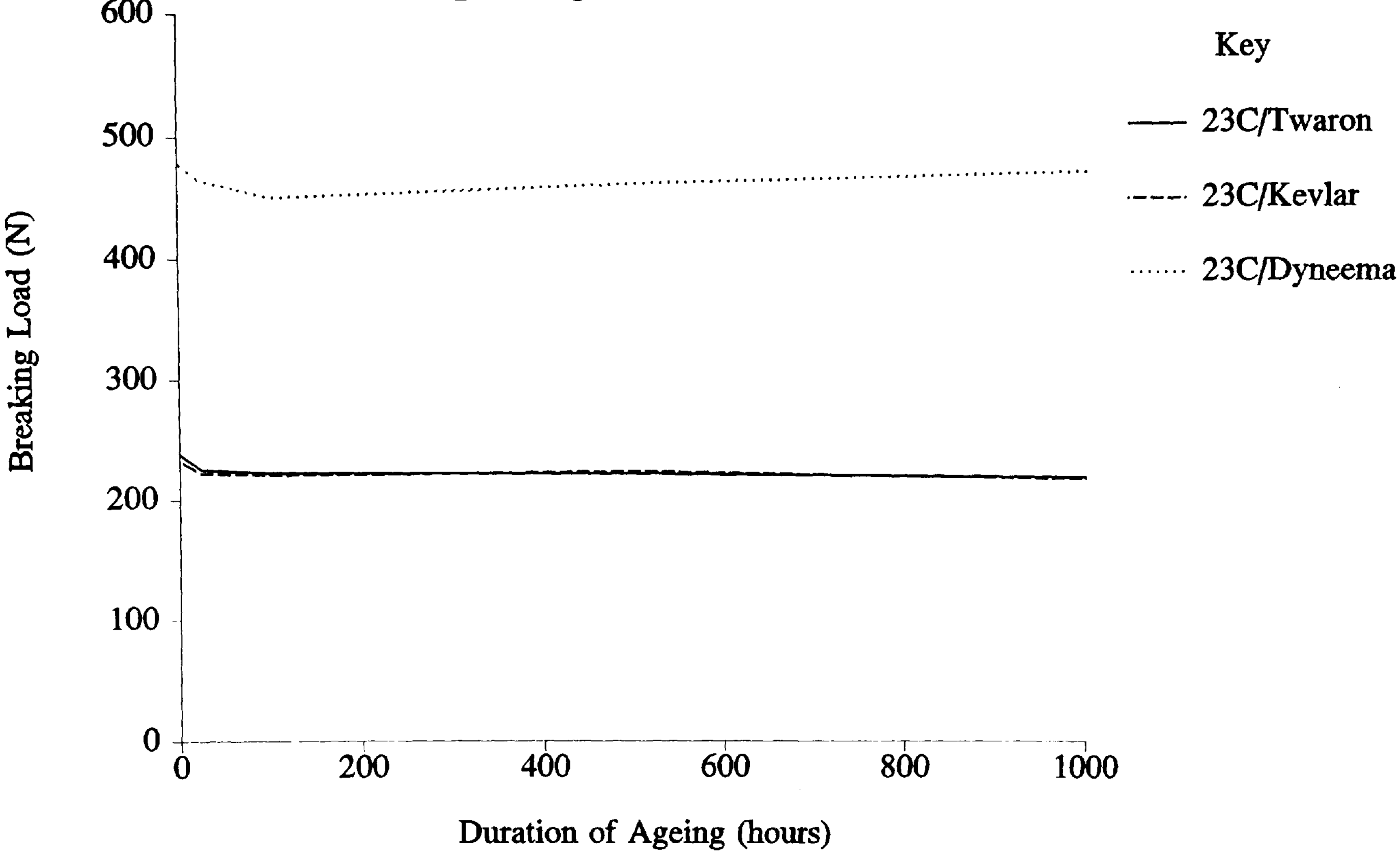


Figure 60 : Tap Water Ageing Test Tensile Results

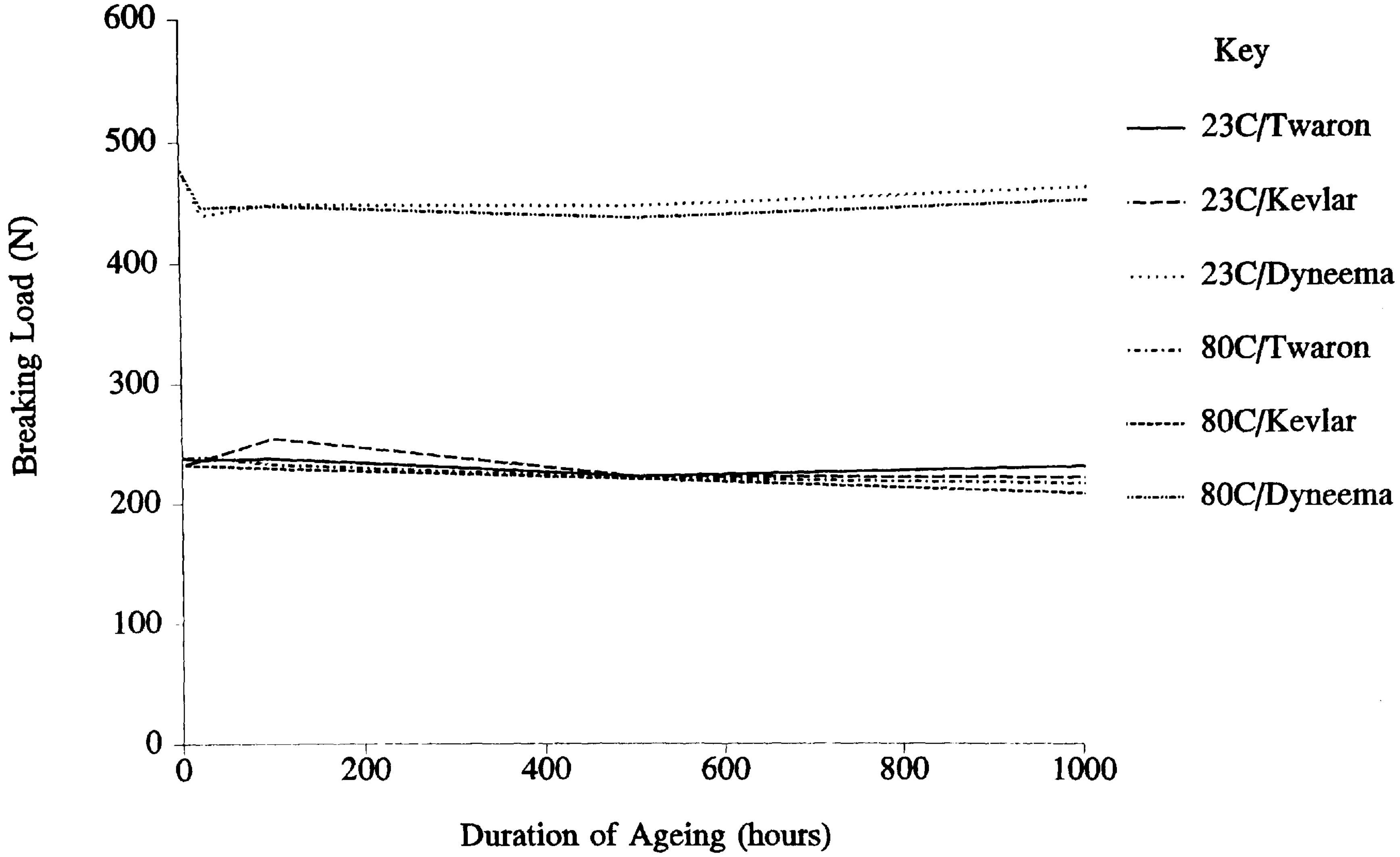


Figure 61 : Thermal Ageing Test Tensile Results

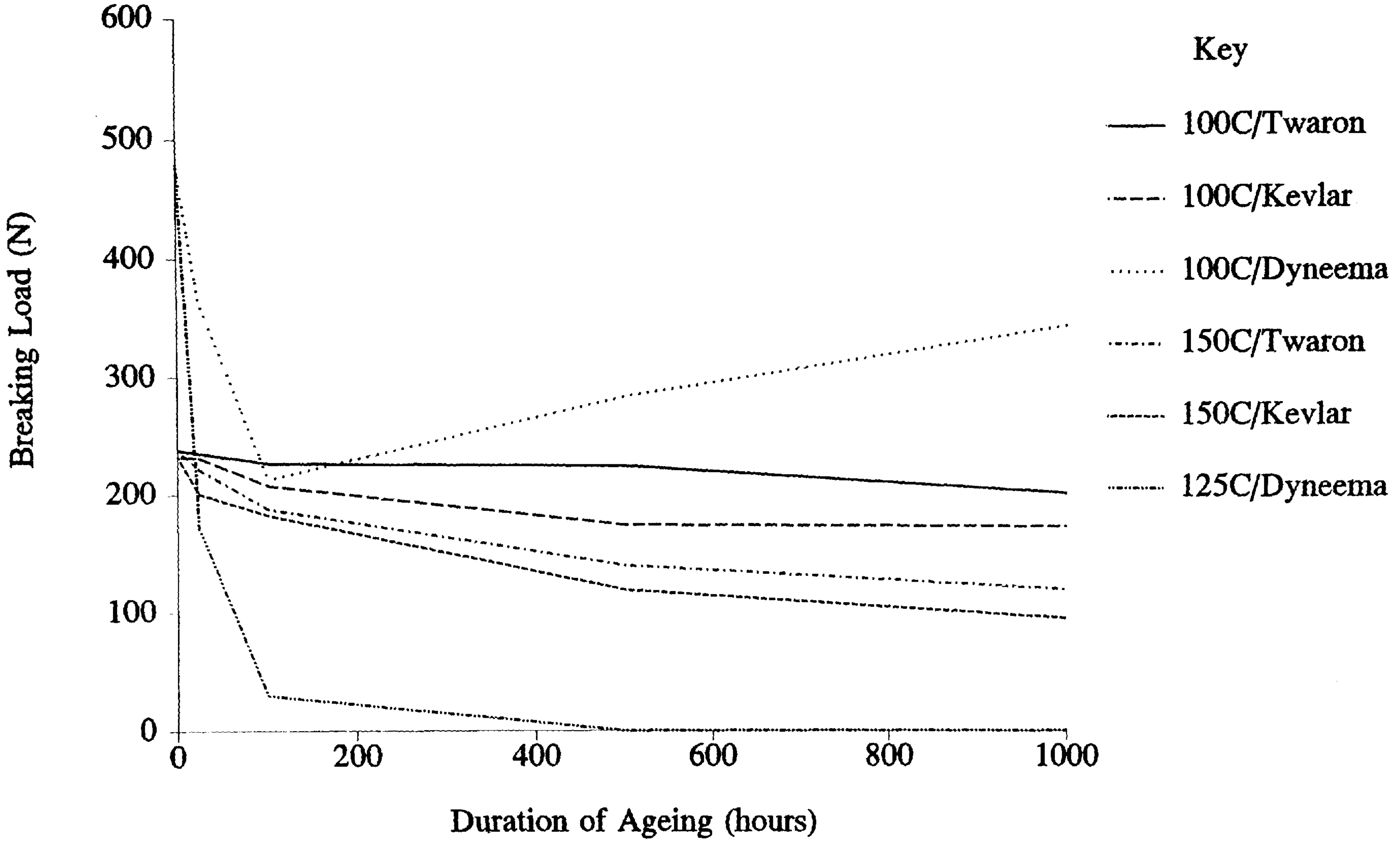


Figure 62 : Ultra Violet Ageing Test Tensile Results

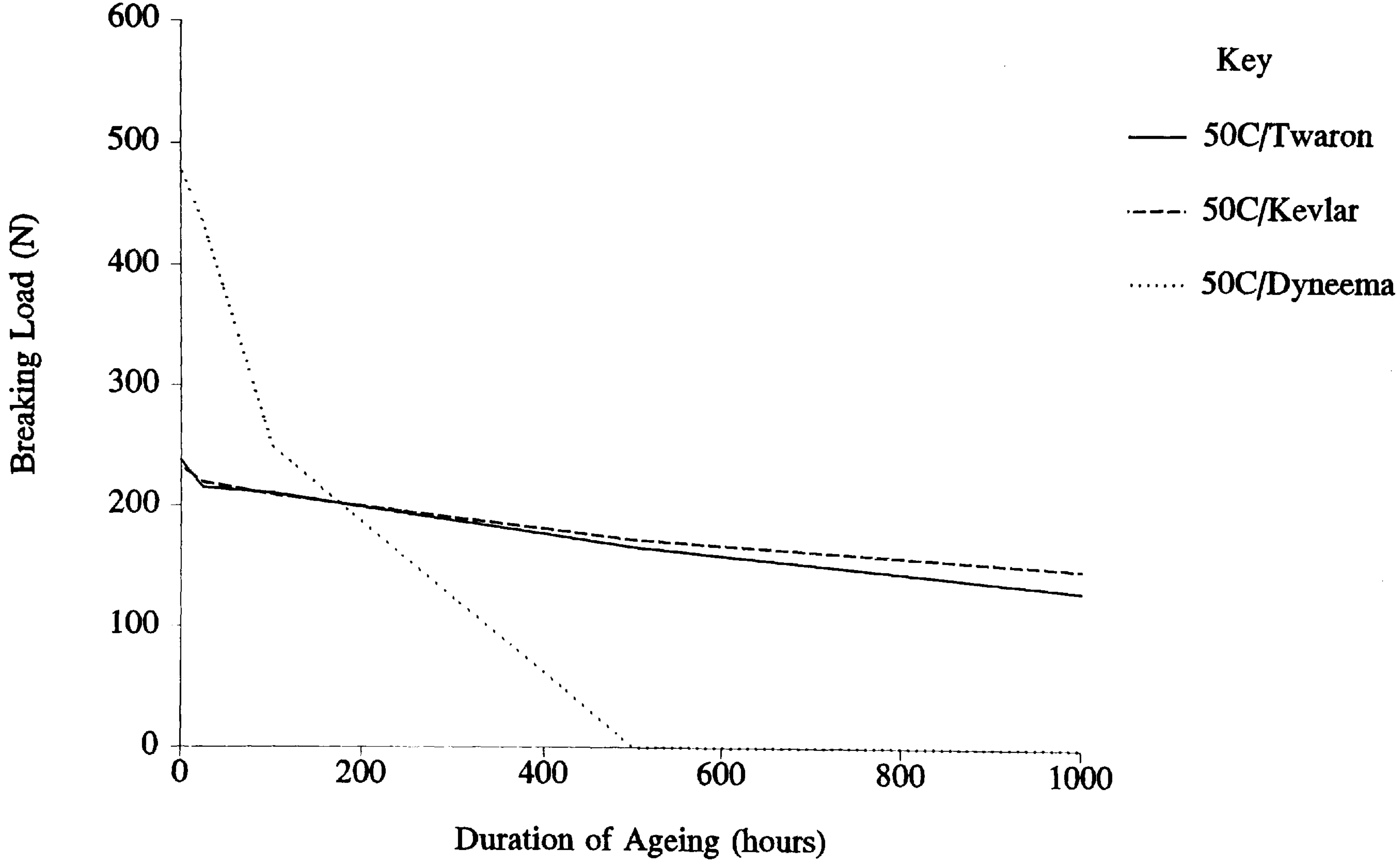


Figure 63 : Saturated Salt Water Ageing Test Tensile Results

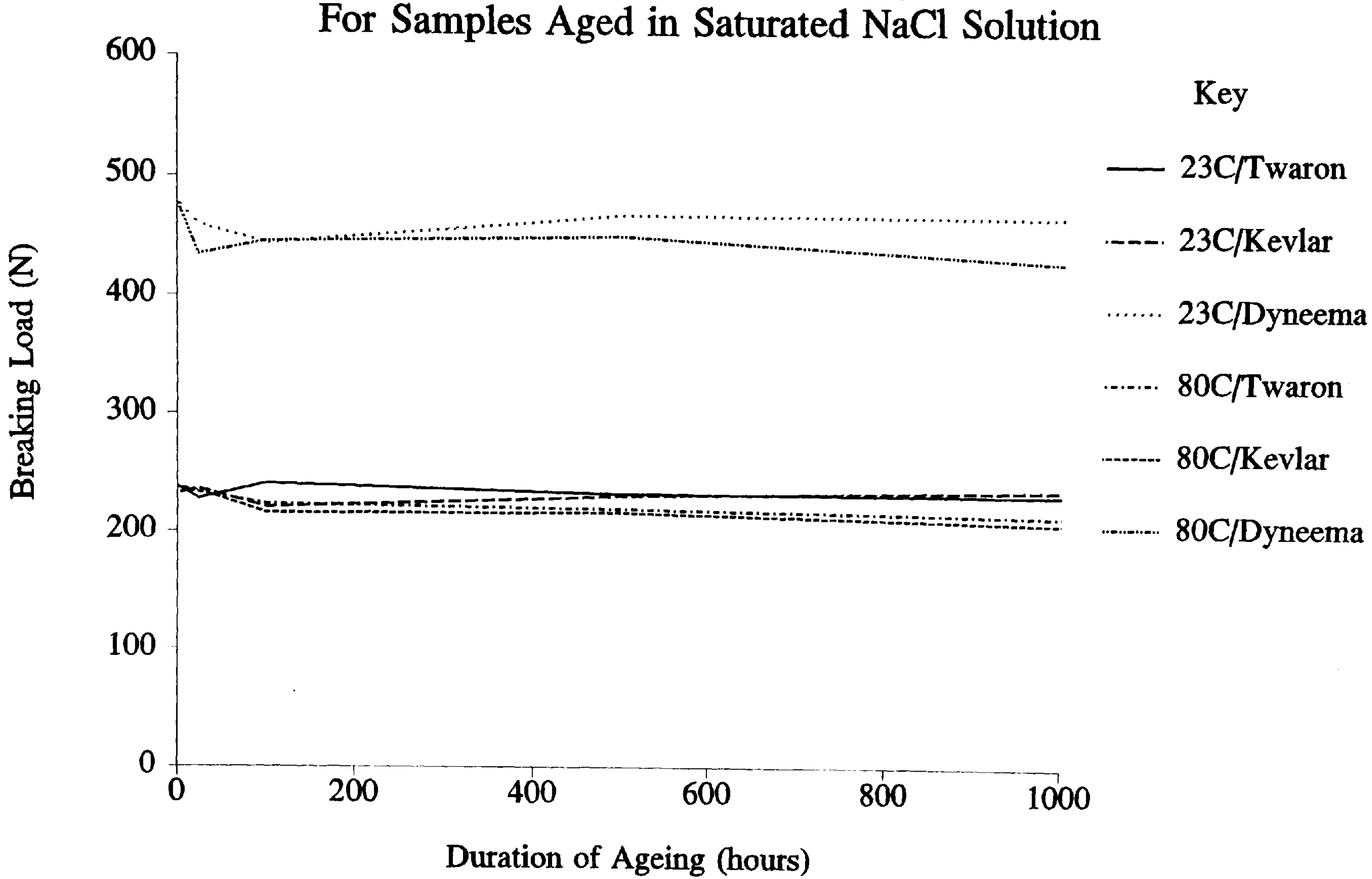


Figure 64 : Aged Yarn Lase Test Results
Load @ 0.5% Strain

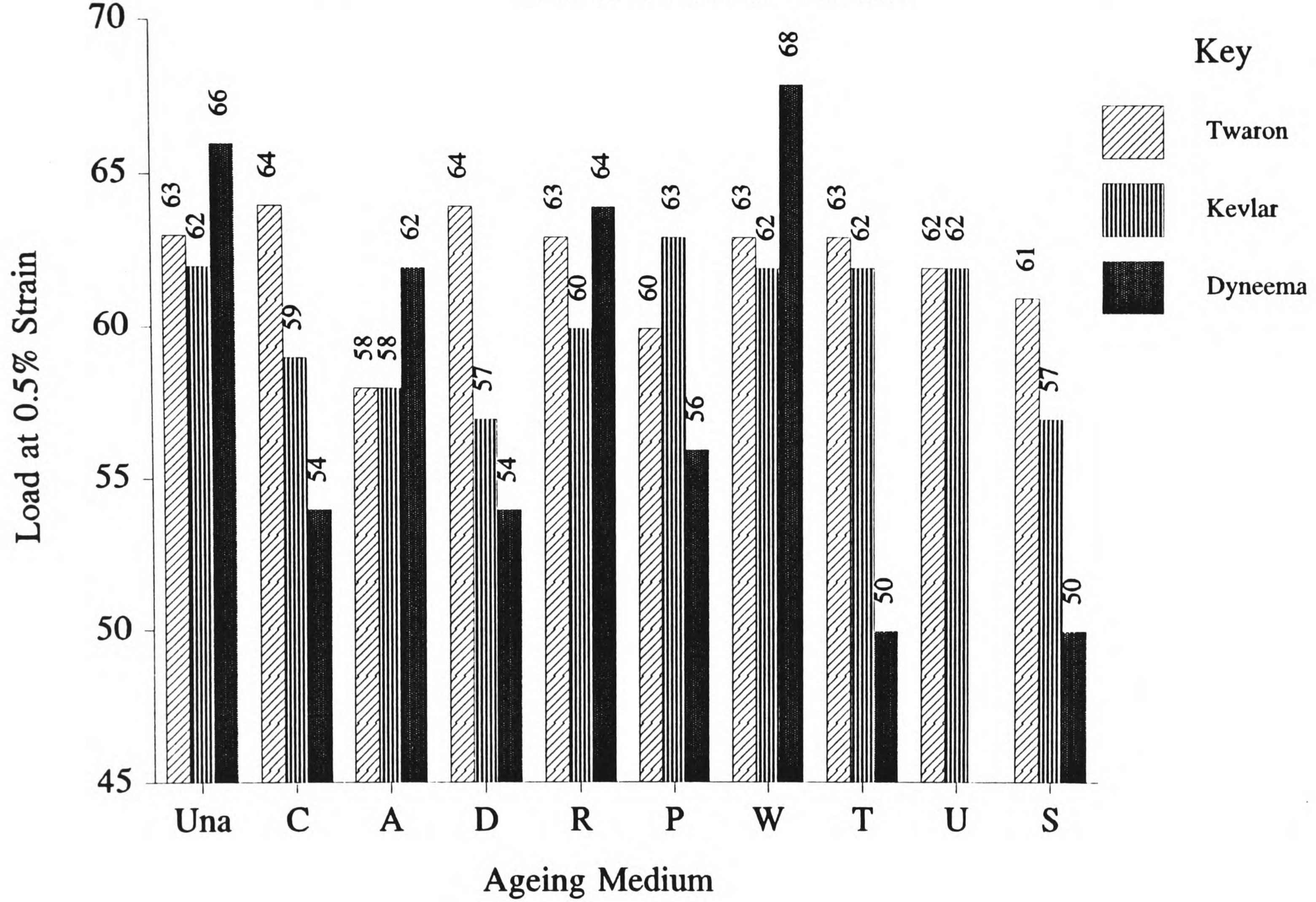


Figure 65 : Aged Yarn Lase Test Results

Young's Modulus

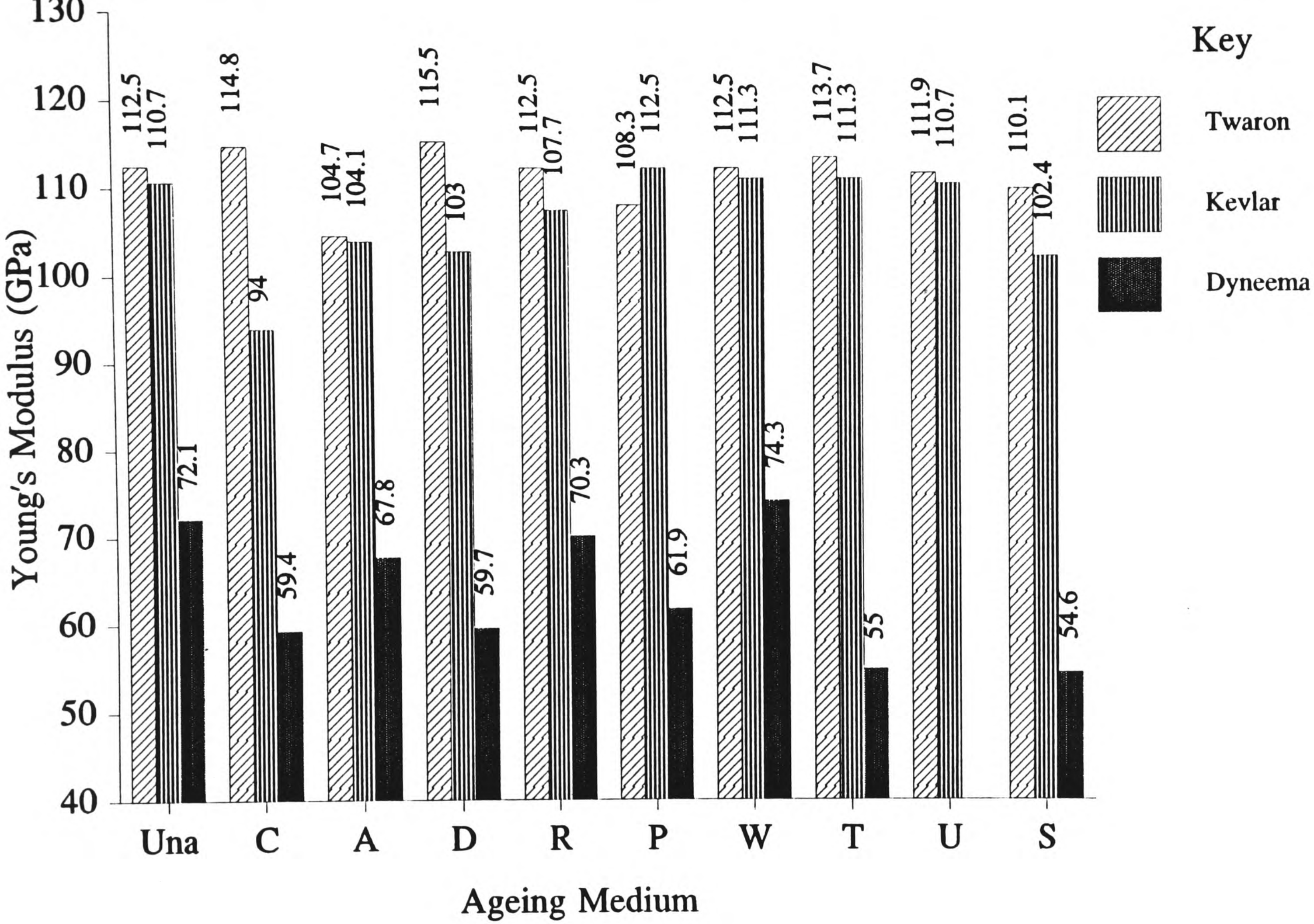


Figure 66 : Aged Yarn Fatigue Test Results

Tensile Breaking Load After Ageing & 10,000 Fatigue Cycles

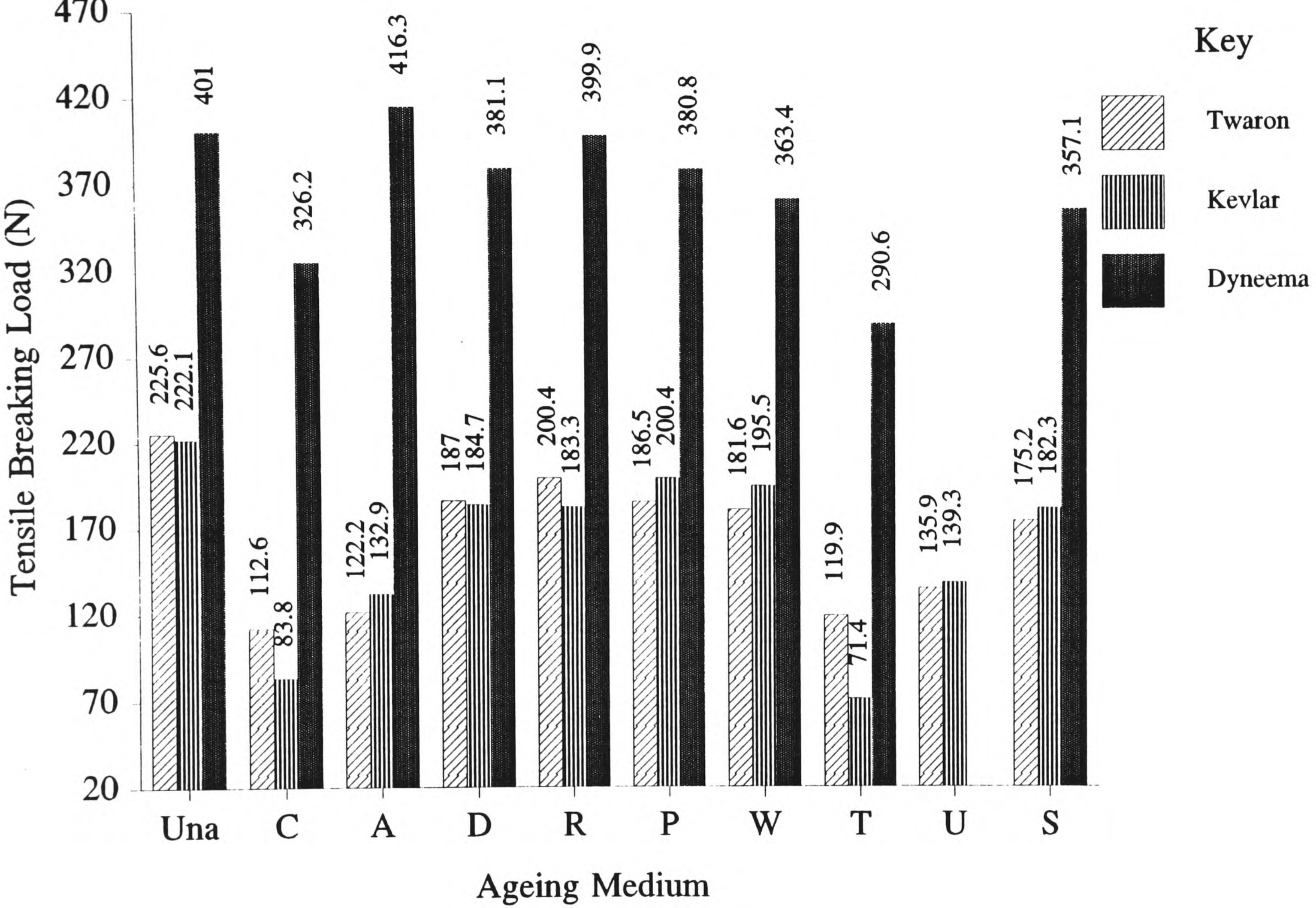


Figure 67 : Aged Yarn Fatigue Test Results

A: Strength of aged fatigue tested yarn as a % of unaged non fatigue tested yarn

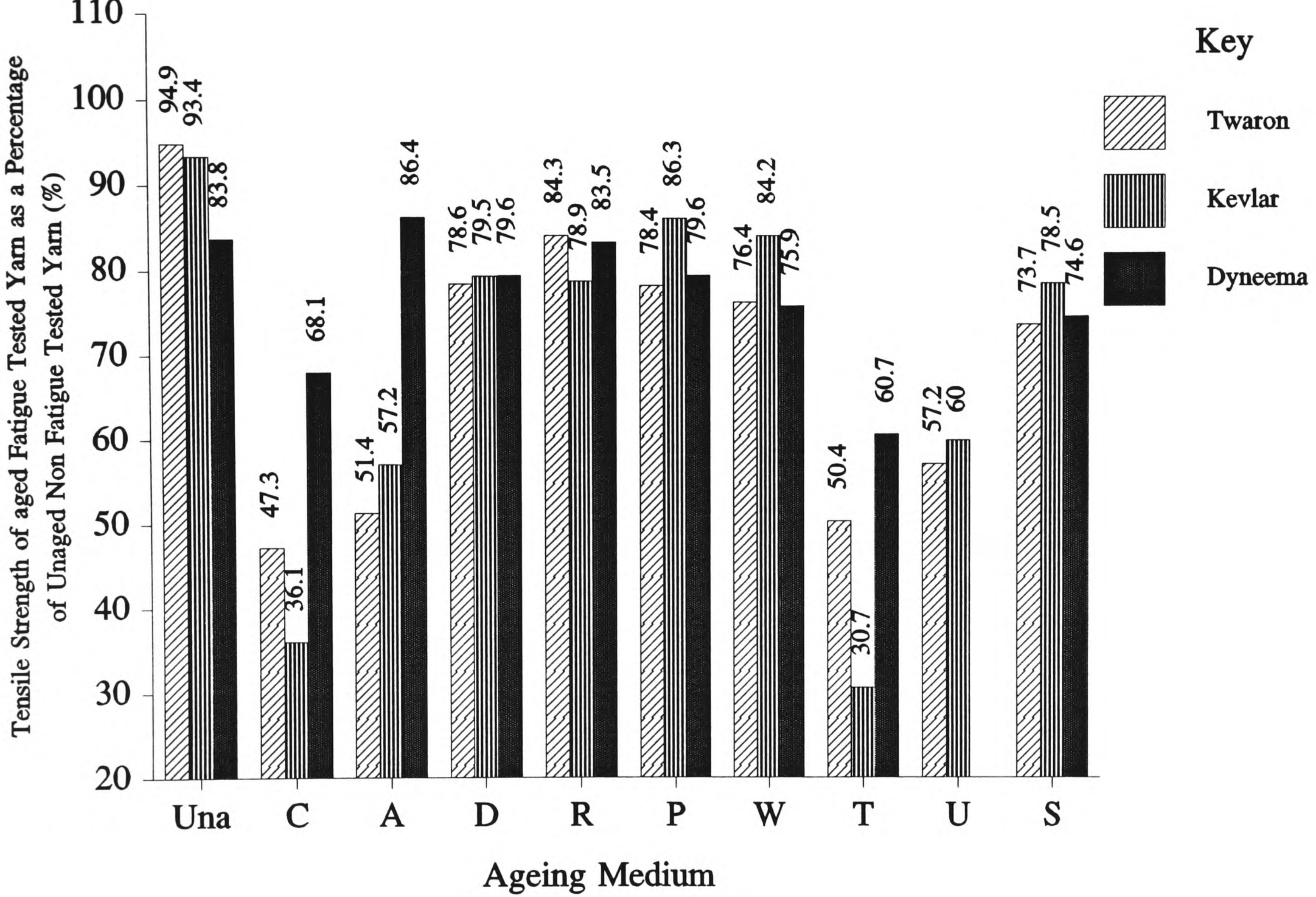


Figure 68 : Aged Yarn Fatigue Test Results

B: Strength of aged fatigue tested yarn as a % of unaged fatigue tested yarn

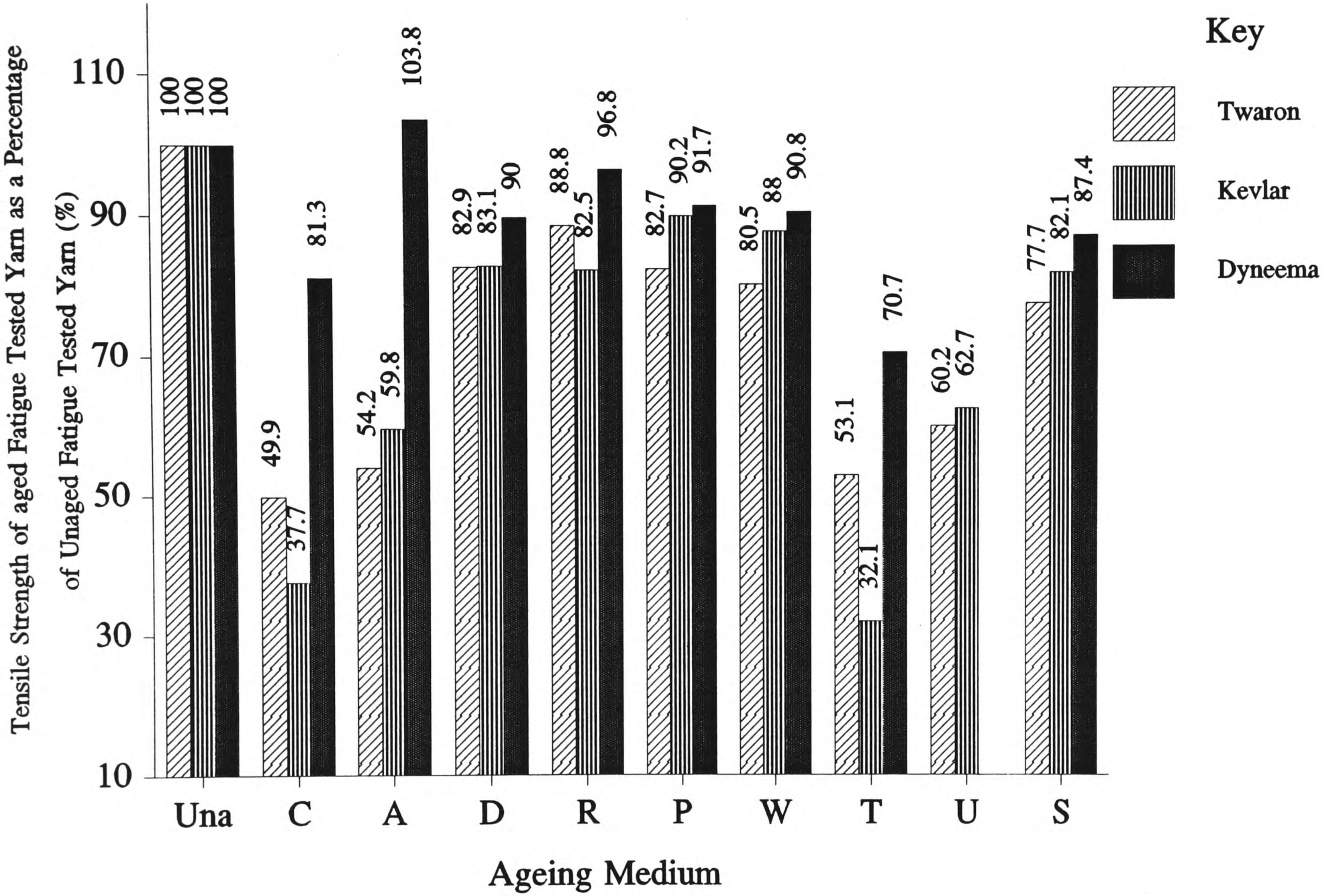


Figure 69 : Environmental Weathering Test Results

For DuPont Kevlar 49 Aged @ 0.5% Strain

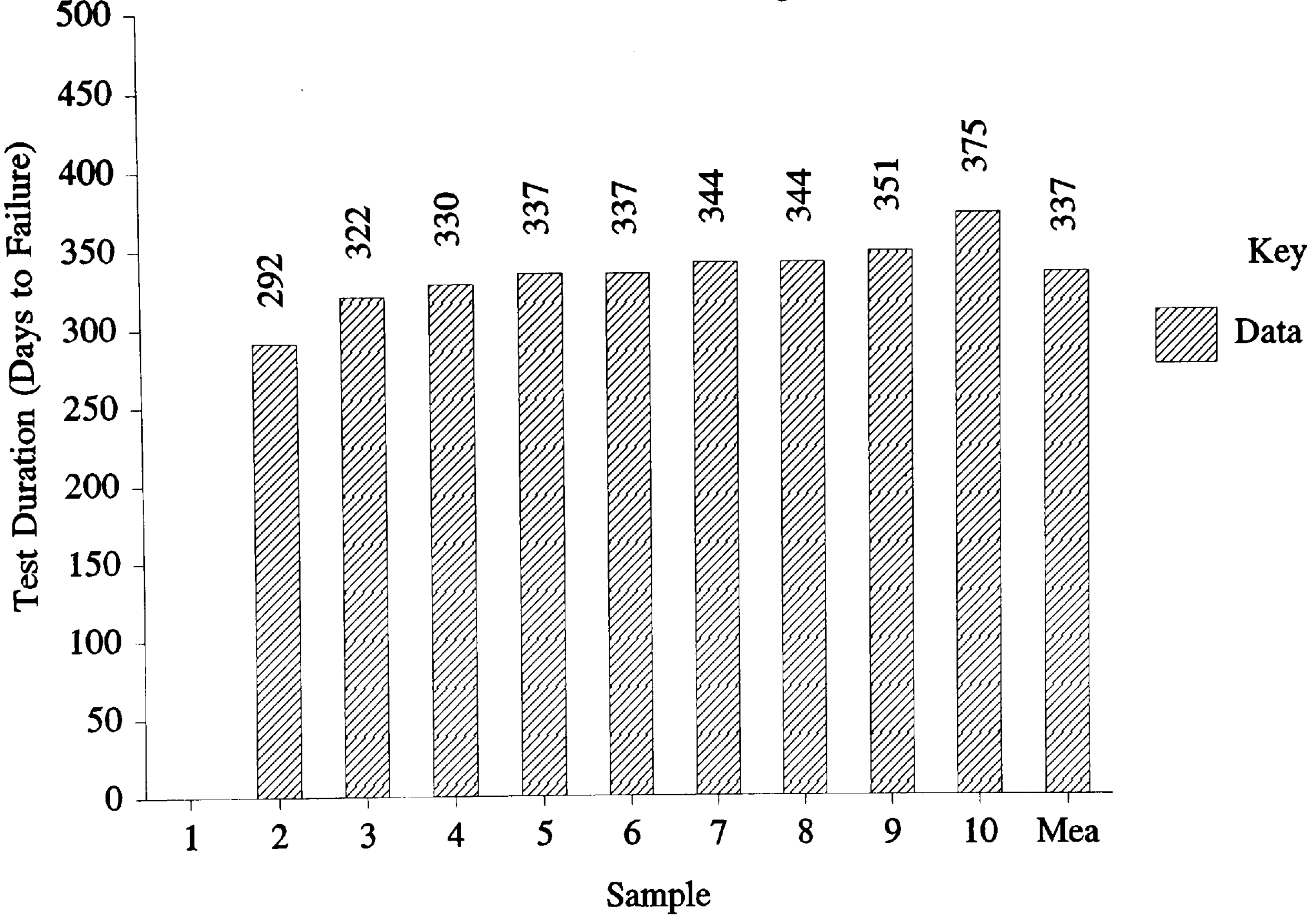


Table 1 : Aramid Combustion Off Gases

Gas Produced	Symbol	mg of Gas per g of Sample
Carbon Monoxide	CO	50
Carbon Dioxide	CO^2	1850
Acetylene	C^2H^2	1
Nitrous Oxide	N^2O	10
Hydrogen Cyanide	HCN	14
Ammonia	NH^3	0.5

Table 2 : Hydrochloric Acid Ageing Scheme

Ageing (molarity & temp)	Duration (hours)	Twaron	Kevlar	Dyneema
0.5 molar @ 23°C	24	T24C23\0.5m	K24C23\0.5m	D24C23\0.5m
	100	T100C23\0.5m	K100C23\0.5m	D100C23\0.5m
	500	T500C23\0.5m	K500C23\0.5m	D500C23\0.5m
	1000	T1000C23\0.5m	K1000C23\0.5m	D1000C23\0.5m
1 molar @ 23°C	24	T24C23\1m	K24C23\1m	D24C23\1m
	100	T100C23\1m	K100C23\1m	D100C23\1m
	500	T100C23\1m	K500C23\1m	D500C23\1m
	1000	T1000C23\1m	K1000C23\1m	D1000C23\1m
1 molar @ 50°C	24	T24C50\1m	K24C50\1m	D24C50\1m
	100	T100C50\1m	K100C50\1m	D100C50\1m
	500	T100C50\1m	K500C50\1m	D500C50\1m
	1000	T1000C50\1m	K1000C50\1m	D1000C50\1m
1 molar @ 80°C	24	T24C80\1m	K24C80\1m	D24C80\1m
	100	T100C80\1m	K100C80\1m	D100C80\1m
	500	T100C80\1m	K500C80\1m	D500C80\1m
	1000	T1000C80\1m	K1000C80\1m	D1000C80\1m

Examples

a. T24C23\0.5m is Akzo Twaron aged in 0.5 molar hydrochloric acid for 24 hours at 23°C.

b. D1000C80\1m is DSM Dyneema aged in 1 molar hydrochloric acid for 1000 hours at 80°C.

Table 3 : Sodium Hydroxide. Detergent, Saturated Salt Water and Tap Water Ageing Schemes

The table below gives the same general ageing scheme for one molar sodium hydroxide ageing, one percent Antarox detergent ageing and saturated sodium chloride salt water solution ageing.

Table 3a : One Molar Sodium Hydroxide Ageing Scheme

Ageing temp	Duration (hours)	Twaron	Kevlar	Dyneema
23°C	24	T24A23	K24A23	D24A23
	100	T100A23	K100A23	D100A23
	500	T500A23	K500A23	D500A23
	1000	T1000A23	K1000A23	D1000A23
80°C	24	T24A80	K24A80	D24A80
	100	T100A80	K100A80	D100A80
	500	T100A80	K500A80	D500A80
	1000	T1000A80	K1000A80	D1000A80

Examples

a. T100A23 is Akzo Twaron aged in saturated salt water solution for 100 hours at 23°C.

b. K1000A80 is DuPont Kevlar 49 aged in saturated salt water solution for 1000 hours at 80°C.

Table 3b : One Percent Antarox Detergent Ageing Scheme

Ageing temp	Duration (hours)	Twaron	Kevlar	Dyneema
23°C	24	T24D23	K24D23	D24D23
	100	T100D23	K100D23	D100D23
	500	T500D23	K500D23	D500D23
	1000	T1000D23	K1000D23	D1000D23
80°C	24	T24D80	K24D80	D24D80
	100	T100D80	K100D80	D100D80
	500	T100D80	K500D80	D500D80
	1000	T1000D80	K1000D80	D1000D80

Examples

a. T100D23 is Akzo Twaron aged in one percent Antarox detergent solution for 100 hours at 23°C.

b. K1000D80 is DuPont Kevlar 49 aged in one percent Antarox detergent solution solution for 1000 hours at 80°C.

Table 3c : Saturated Sodium Chloride Salt Water Solution Ageing.

Ageing temp	Duration (hours)	Twaron	Kevlar	Dyneema
23°C	24	T24S23	K24S23	D24S23
	100	T100S23	K100S23	D100S23
	500	T500S23	K500S23	D500S23
	1000	T1000S23	K1000S23	D1000S23
80°C	24	T24S80	K24S80	D24S80
	100	T100S80	K100S80	D100S80
	500	T100S80	K500S80	D500S80
	1000	T1000S80	K1000S80	D1000S80

<u>Examples</u>

a. D100S23 is DSM Dyneema aged in saturated sodium chloride salt solution for 100 hours at 23°C.

b. K500S80 is DuPont Kevlar 49 aged in saturated sodium chloride salt solution solution for 500 hours at 80°C.

Table 4 : Thermal Ageing Scheme

Ageing temp	Duration (hours)	Twaron	Kevlar	Dyneema
100°C	24	T24H100	K24H100	D24H100
	100	T100H100	K100H100	D100H100
	500	T500H100	K500H100	D500H100
	1000	T1000H100	K1000H100	D1000H100
125°C	24	N/A	N/A	D24H125
	100	N/A	N/A	D100H125
	500	N/A	N/A	D500H125
	1000	N/A	N/A	D1000H125
150°C	24	T24H150	K24H150	N/A
	100	T100H150	K100H150	N/A
	500	T500H150	K500H150	N/A
	1000	T1000H150	K1000H150	N/A

Examples

a. T500H100 is Akzo Twaron thermally aged for 500 hours at 100°C.

b. K1000H150 is DuPont Kevlar 49 thermally aged for 1000 hours at 150°C.

Table 5 : Ultra Violet Ageing Scheme

Ageing (@ temp)	Duration (hours)	Twaron	Kevlar	Dyneema
50°C, Cyclic ageing in 4 hour cycles of condensation and four hour cycles of u.v. radiation.	24	T24U50	K24U50	D24U50
	100	T100U50	K100U50	D100U50
	500	T500U50	K500U50	D500U50
	1000	T1000U50	K1000U50	D1000U50

Examples

a. T500U50 is Akzo Twaron aged under u.v. cycling conditions for 500 hours at 50°C.

b. D1000U50 is DSM Dyneema aged under u.v. cycling conditions for 1000 hours at 50oC.

Table 6 : Diesel and Petrol Ageing Scheme

The table below gives the same general ageing scheme for DERV diesel oil ageing ageing and premium unleaded petrol ageing.

Table 6a : DERV Diesel Oil Ageing Scheme

Ageing temp	Duration (hours)	Twaron	Kevlar	Dyneema
23°C	24	T24R23	K24R23	D24R23
	100	T100R23	K100R23	D100R23
	500	T500R23	K500R23	D500R23
	1000	T1000R23	K1000R23	D1000R23

Examples

a. T24R23 is Akzo Twaron aged in DERV diesel oil for 24 hours at 23°C.

b. K1000R23 is DuPont Kevlar 49 aged in DERV diesel oil for 1000 hours at 23°C.

Table 6b : Premium Unleaded Petrol Ageing Scheme

Ageing temp	Duration (hours)	Twaron	Kevlar	Dyneema
23°C	24	T24P23	K24P23	D24P23
	100	T100P23	K100P23	D100P23
	500	T500P23	K500P23	D500P23
	1000	T1000P23	K1000P23	D1000P23

Examples

a. T24P23 is Akzo Twaron aged in premium unleaded petrol for 24 hours at 23°C.

b. K1000P23 is DuPont Kevlar 49 aged in premium unleaded petrol for 1000 hours at 23°C.

Table 7 : Tensile Test Results

All samples tested in accordance with the General Yarn Tensile Test Method

Table 7a : Tensile Test Results for Akzo Twaron (1610 dtex)

Test Results (100 Samples)	Tensile Breaking Load (N)	UTS (MPa)
Min	216.3	1931.3
Max	258.6	2308.9
Mean	237.8	2123.2
S.D.	9.2	81.9

Table 7b : Tensile Test Results for Kevlar 49 (1580 dtex)

Test Results (100 Samples)	Tensile Breaking Load (N)	UTS (MPa)
Min	209.8	1873.2
Max	262.5	2343.8
Mean	232.1	2072.2
S.D.	9.4	84.0

Table 7c : Tensile Test Results for DSM Dyneema SK65 (1760 dtex)

Test Results (100 Samples)	Tensile Breaking Load (N)	UTS (MPa)
Min	382.8	2535.3
Max	527.1	3490.9
Mean	478.3	3167.3
S.D.	37.9	250.8

Table 8 : Tensile Test Results Data Groups

The tables below give the data groups used in the Distribution of Tensile Test Results Histograms *(figures 27, 28, 29 & 30)*.

Table 8a : Data Groups for Akzo Twaron Type (1610 dtex)

Group Number	Group Interval (N)	Group Limits (N)
1	4.9	215.0-219.9
2	4.9	220.0-224.9
3	4.9	225.0-229.9
4	4.9	230.0-234.9
5	4.9	235.0-239.9
6	4.9	240.0-244.9
7	4.9	245.0-249.9
8	4.9	250.0-254.9
9	4.9	255.0-259.9

Table 8b : Data Groups for DuPont Kevlar 49 (1580 dtex)

Group Number	Group Interval (N)	Group Limits (N)
1	4.9	205.0-219.9
2	4.9	210.0-214.9
3	4.9	215.0-219.9
4	4.9	220.0-224.9
5	4.9	225.0-229.9
6	4.9	230.0-234.9
7	4.9	235.0-239.9
8	4.9	240.0-244.9
9	4.9	245.0-249.9
10	4.9	250.0-254.9
11	4.9	255.0-259.9
12	4.9	260.0-264.9

Table 8c : Data Groups for DSM Dyneema SK65 (1760 dtex)

Group Number	Group Interval (N)	Group Limits (N)
1	9.9	380.0-389.9
2	9.9	390.0-399.9
3	9.9	400.0-409.9
4	9.9	410.0-419.9
5	9.9	420.0-429.9
6	9.9	430.0-439.9
7	9.9	440.0-449.9
8	9.9	450.0-459.9
9	9.9	460.0-469.9
10	9.9	470.0-479.9
11	9.9	480.0-489.9
12	9.9	490.0-499.9
13	9.9	500.0-509.9
14	9.9	510.0-519.9
15	9.9	520.0-529.9

Table 9 : LASE Test Results

All samples tested in accordance with the Yarn LASE Test Method

Material (10 Samples)	Load @ 0.5% Strain (N)	S.D.
Akzo Twaron (1580 dtex)	63	2.80
DuPont Kevlar 49 (1580 dtex)	62	2.95
DSM Dyneema SK65 (1760 dtex)	66	4.23
Owens Corning OFY 680 (7294 dtex)	88	3.77
Jointed Kevlar 49	63 (As per Kevlar 49)	N/A

Table 10 : Material Yarn Creep Test Results

All samples tested in accordance with the Material Yarn Creep Test Method

10a : Creep Test Results for Akzo Twaron (1610 dtex)

Creep Test Duration		Creep	S.D.
Hours	Log Seconds	(%)	(%)
0		0.000	0.000
168	5.7816	0.022	0.017
504	6.2587	0.023	0.032
1176	6.6267	0.033	0.021
1848	6.8230	0.044	0.019
2520	6.9577	0.046	0.014
3192	7.0604	0.056	0.017
3864	7.1433	0.066	0.021
5208	7.2729	0.071	0.025
6552	7.3726	0.073	0.021

10b : Creep Test Results for DuPont Kevlar 49 (1580 dtex)

Creep Test Duration		Creep	S.D.
Hours	Log Seconds	(%)	(%)
0		0.000	0.000
168	5.7816	0.023	0.071
504	6.2587	0.044	0.021
1176	6.6267	0.045	0.024
1848	6.8230	0.054	0.024
2520	6.9577	0.059	0.016
3192	7.0604	0.063	0.014
3864	7.1433	0.070	0.018
5208	7.2729	0.079	0.017
6552	7.3726	0.081	0.016

10c : Creep Test Results for DSM Dyneema SK65 (1760 dtex)

Creep Test Duration		Creep	S.D.
Hours	Log Seconds	(%)	(%)
0		0.000	0.000
168	5.7816	0.281	0.053
504	6.2587	0.385	0.039
1176	6.6267	0.500	0.040
1848	6.8230	0.612	0.041
2520	6.9577	0.739	0.056
3192	7.0604	0.860	0.061
3864	7.1433	0.958	0.067
5208	7.2729	1.225	0.069
6552	7.3726	1.366	0.080

10d : Creep Test Results for Owens Corning OFY 680 (7294 dtex)

Creep Test Duration		Creep	S.D.
Hours	Log Seconds	(%)	(%)
0		0.000	0.000
168	5.7816	0.011	0.015
504	6.2587	0.019	0.017
1176	6.6267	0.020	0.016
1848	6.8230	0.021	0.013
2520	6.9577	0.027	0.014
3192	7.0604	0.036	0.015
3864	7.1433	0.037	0.015
5208	7.2729	0.037	0.013

10e : Creep Test Results for Jointed Kevlar 49 (1580 dtex)

Creep Test Duration		Creep	S.D.
Hours	Log Seconds	(%)	(%)
0		0.000	0.000
168	5.7816	0.086	0.026
504	6.2587	0.117	0.032
1176	6.6267	0.140	0.048
1848	6.8230	0.147	0.041
2520	6.9577	0.152	0.039
3192	7.0604	0.158	0.038
3864	7.1433	0.173	0.044
5208	7.2729	0.181	0.050

Table 11 : Material Yarn Creep Test Results

All samples tested in accordance with the Material Yarn Creep Test Method, for data collected up to 5208 hours test duration.

Material (10 Samples)	Creep Rate (%/dec)
Akzo Twaron (1580 dtex)	0.033
DuPont Kevlar 49 (1580 dtex)	0.033
DSM Dyneema SK65 (1760 dtex)	0.057 (average)
Owens Corning OFY 680 (7294 dtex)	0.018
Jointed Kevlar 49	0.060 (gauge length dependant)

Table 12 : Cable Creep Test Results

All samples tested in accordance with the Material Cable Test Method, for data collected up to 180 hours test duration. Creep tests base on cable containing 22 ends of Akzo Twaron Type 1055 High Modulus dry aramid stranded around a smooth taped optical core.

Cable Samples	Creep After 40 Years (%)	Creep Rate (%/dec)	S.D. in Creep Rate (%)	Initial Elongation (%)
1	0.146	0.016	N/A	1.578
2	0.164	0.018	N/A	1.452
3	0.146	0.016	N/A	1.324
Average of samples 1,2 &3	0.152	0.0167	0.01155	1.451

Table 13 : Fatigue Test Results

Number of Fatigue Cycles	Average Breaking Load of Six Samples (N)									
	Twaron		Kevlar		Dyneema		Jointed K49		OC OFY 680	
	UTS	SD	UTS	SD	UTS	SD	UTS	SD	UTS	SD
1	234	8	239	9	429	12	212	12	581	24
10	230	6	236	11	426	9	222	22	594	7
100	231	8	231	2	426	14	230	8	564	16
1000	230	9	225	13	426	20	239	9	533	33
10000	226	7	222	14	401	10	217	17	454	39
100000	160	35	165	57	352	40	159	20	252	52
1000000	82	46	83	49	288	126	F	F	F	F

F = Sample failure during fatigue testing.

Table 14 : Summary of Jointed Aramid Results

Test	Result
LASE	Load @ 0.5% Strain = 65N, SD 0.1N Strain @ 62N = 0.484 %
TENSILE	Mean Breaking Load (N) = 206 N, SD 15N (5 Samples) Mean Breaking Load = 89% of Unspliced Mean
FATIGUE	Number of cycles to splice pull apart = 328764

Table 15 : Akzo Twaron Acid Ageing Test Results

15a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave SD Break Load (N)
T24C23\0.5m	25	219.7	251.2	194.3	14.1
T100C23\0.5m	25	219.4	244.4	198.8	9.6
T500C23\0.5m	25	203.1	232.1	171.9	16.2
T1000C23\0.5m	25	191.2	231.2	152.1	22.2
T24C23\1m	25	226.4	243.3	196.8	13.2
T100C23\1m	25	202.9	243.5	163.7	18.6
T500C23\1m	25	144.1	187.6	112.2	22.9
T1000C23\1m	25	99.4	149.2	81.0	14.6
T24C50\1m	25	191.3	250.6	142.9	29.6
T100C50\1m	25	154.6	194.2	100.2	31.8
T500C50\1m	25	100.4	137.8	61.0	19.0
T1000C50\1m	25	67.2	91.2	41.0	13.5
T24C80\1m	25	80.8	142.5	44.0	23.9
T100C80\1m	25	55.1	75.1	45.0	9.6
T500C80\1m	25	N/A	N/A	N/A	N/A
T1000C80\1m	25	N/A	N/A	N/A	N/A

15b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
T24C23\0.5m	24	-1.353	±2.064	**Accept**	*Reject*
T100C23\0.5m	24	-3.976	±2.064	*Reject*	**Accept**
T500C23\0.5m	24	-3.107	±2.064	*Reject*	**Accept**
T1000C23\0.5m	24	-2.702	±2.064	*Reject*	**Accept**
T24C23\1m	24	-1.387	±2.064	**Accept**	*Reject*
T100C23\1m	24	-2.562	±2.064	*Reject*	**Accept**
T500C23\1m	24	-5.229	±2.064	*Reject*	**Accept**
T1000C23\1m	24	-14.377	±2.064	*Reject*	**Accept**
T24C50\1m	24	-1.889	±2.064	**Accept**	*Reject*
T100C50\1m	24	-3.100	±2.064	*Reject*	**Accept**
T500C50\1m	24	-9.787	±2.064	*Reject*	**Accept**
T1000C50\1m	24	-19.977	±2.064	*Reject*	**Accept**
T24C80\1m	24	-8.307	±2.064	*Reject*	**Accept**
T100C80\1m	24	-40.115	±2.064	*Reject*	**Accept**
T500C80\1m	24	N/A	±2.064	N/A	N/A
T1000C80\1m	24	N/A	±2.064	N/A	N/A

Table 16 : DuPont Kevlar 49 Acid Ageing Test Results

16a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave SD Break Load (N)
K24C23\0.5m	25	219.7	251.2	194.3	14.1
K100C23\0.5m	25	200.4	200.4	168.2	14.7
K500C23\0.5m	25	156.8	190.3	115.8	22.7
K1000C23\0.5m	25	160.3	199.9	119.6	19.7
K24C23\1m	25	217.5	245.6	197.9	11.3
K100C23\1m	25	189.1	211.7	151.0	17.3
K500C23\1m	25	128.8	128.8	97.0	18.3
K1000C23\1m	25	97.9	124.9	60.0	14.0
K24C50\1m	25	157.8	188.8	126.8	16.9
K100C50\1m	25	109.6	150.7	79.0	19.7
K500C50\1m	25	73.4	112.9	43.0	17.0
K1000C50\1m	25	46.5	78.0	15.0	12.4
K24C80\1m	25	72.0	101.4	51.0	13.3
K100C80\1m	25	40.0	57.0	20.0	9.0
K500C80\1m	25	N/A	N/A	N/A	N/A
K1000C80\1m	25	N/A	N/A	N/A	N/A

16b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
K24C23\0.5m	24	-1.353	±2.064	**Accept**	*Reject*
K100C23\0.5m	24	-3.249	±2.064	*Reject*	**Accept**
K500C23\0.5m	24	-4.247	±2.064	*Reject*	**Accept**
K1000C23\0.5m	24	-4.881	±2.064	*Reject*	**Accept**
K24C23\1m	24	-2.320	±2.064	*Reject*	**Reject**
K100C23\1m	24	-3.488	±2.064	*Reject*	**Accept**
K500C23\1m	24	-7.761	±2.064	*Reject*	**Accept**
K1000C23\1m	24	-14.945	±2.064	*Reject*	**Accept**
K24C50\1m	24	-6.221	±2.064	*Reject*	**Reject**
K100C50\1m	24	-8.330	±2.064	*Reject*	**Accept**
K500C50\1m	24	-13.187	±2.064	*Reject*	**Accept**
K1000C50\1m	24	-24.976	±2.064	*Reject*	**Accept**
K24C80\1m	24	-15.548	±2.064	*Reject*	**Accept**
K100C80\1m	24	-47.678	±2.064	*Reject*	**Accept**
K500C80\1m	24	N/A	±2.064	N/A	N/A
K1000C80\1m	24	N/A	±2.064	N/A	N/A

Table 17 : DSM Dyneema SK65 Acid Ageing Test Results

17a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave SD Break Load (N)
D24C23\0.5m	25	479.9	516.2	437.3	19.0
D100C23\0.5m	25	473.7	506.3	449.0	13.4
D500C23\0.5m	25	479.5	518.7	447.1	17.9
D1000C23\0.5m	25	485.1	510.7	459.9	15.0
D24C23\1m	25	461.2	508.1	341.7	32.8
D100C23\1m	25	456.7	484.2	402.9	22.8
D500C23\1m	25	454.2	483.3	391.0	18.7
D1000C23\1m	25	446.7	482.6	412.2	20.9
D24C50\1m	25	472.7	513.8	414.5	21.2
D100C50\1m	25	452.4	500.3	269.0	47.5
D500C50\1m	25	472.3	506.0	413.1	18.4
D1000C50\1m	25	469.4	493.4	442.9	16.0
D24C80\1m	25	458.1	486.9	412.9	17.5
D100C80\1m	25	450.0	473.6	414.7	16.1
D500C80\1m	25	N/A	N/A	N/A	N/A
D1000C80\1m	25	N/A	N/A	N/A	N/A

17b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
D24C23\0.5m	24	0.112	±2.064	**Accept**	*Reject*
D100C23\0.5m	24	-0.543	±2.064	**Accept**	*Reject*
D500C23\0.5m	24	0.091	±2.064	**Accept**	*Reject*
D1000C23\0.5m	24	0.683	±2.064	**Accept**	*Reject*
D24C23\1m	24	-0.616	±2.064	**Accept**	*Reject*
D100C23\1m	24	-1.213	±2.064	**Accept**	*Reject*
D500C23\1m	24	-1.758	±2.064	**Accept**	*Reject*
D1000C23\1m	24	-1.989	±2.064	**Accept**	*Reject*
D24C50\1m	24	-0.342	±2.064	**Accept**	*Reject*
D100C50\1m	24	-0.609	±2.064	**Accept**	*Reject*
D500C50\1m	24	-0.447	±2.064	**Accept**	*Reject*
D1000C50\1m	24	-0.808	±2.064	**Accept**	*Reject*
D24C80\1m	24	-1.621	±2.064	**Accept**	*Reject*
D100C80\1m	24	-2.547	±2.064	*Reject*	**Accept**
D500C80\1m	24	N/A	±2.064	N/A	N/A
D1000C80\1m	24	N/A	±2.064	N/A	N/A

Table 18 : Akzo Twaron Alkali Ageing Test Results

18a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
T24A23	25	228.0	250.8	210.7	10.0
T100A23	25	206.9	224.1	194.0	7.6
T500A23	25	174.2	214.1	136.5	19.5
T1000A23	25	152.9	190.6	123.1	16.8
T24A80	25	134.6	171.1	89.0	22.5
T100A80	25	51.5	75.0	23.0	12.3
T500A80	25	28.6	43.0	21.0	5.3
T1000A80	25	N/A	N/A	N/A	N/A

18b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
T24A23	24	-1.959	± 2.064	**Accept**	*Reject*
T100A23	24	-11.723	± 2.064	*Reject*	**Accept**
T500A23	24	-4.394	± 2.064	*Reject*	**Accept**
T1000A23	24	-7.196	± 2.064	*Reject*	**Accept**
T24A80	24	-5.901	± 2.064	*Reject*	**Accept**
T100A80	24	-25.381	± 2.064	*Reject*	**Accept**
T500A80	24	-619.543	± 2.064	*Reject*	**Accept**
T1000A80	24	N/A	± 2.064	N/A	N/A

Table 19 : DuPont Kevlar 49 Alkali Ageing Test Results

19a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
K24A23	25	223.8	232.8	212.0	9.8
K100A23	25	197.0	197.0	163.0	14.7
K500A23	25	166.4	212.0	134.6	23.3
K1000A23	25	138.4	200.2	89.0	25.6
K24A80	25	93.1	138.6	54.0	21.7
K100A80	25	41.2	59.0	24.0	9.3
K500A80	25	21.9	31.0	16.0	3.6
K1000A80	25	N/A	N/A	N/A	N/A

19b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
K24A23	24	-1.716	±2.064	**Accept**	*Reject*
K100A23	24	-3.635	±2.064	*Reject*	**Accept**
K500A23	24	-8.325	±2.064	*Reject*	**Accept**
K1000A23	24	-4.549	±2.064	*Reject*	**Accept**
K24A80	24	-8.325	±2.064	*Reject*	**Accept**
K100A80	24	-44.414	±2.064	*Reject*	**Accept**
K500A80	24	151.156	±2.064	*Reject*	**Accept**
K1000A80	24	N/A	±2.064	N/A	N/A

Table 20 : DSM Dyneema SK65 Alkali Ageing Test Results

20a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
D24A23	25	471.5	479.3	440.5	14.4
D100A23	25	462.0	497.1	437.5	15.3
D500A23	25	479.2	458.4	434.3	14.3
D1000A23	25	447.9	486.0	368.5	25.1
D24A80	25	454.4	485.3	389.9	22.0
D100A80	25	446.8	477.7	409.2	19.4
D500A80	25	445.9	477.5	409.7	18.9
D1000A80	25	438.2	471.8	406.3	17.9

20b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
D24A23	24	-0.728	± 2.064	**Accept**	*Reject*
D100A23	24	-1.577	± 2.064	**Accept**	*Reject*
D500A23	24	-2.150	± 2.064	*Reject*	**Accept**
D1000A23	24	-1.509	± 2.064	**Accept**	*Reject*
D24A80	24	-1.403	± 2.064	**Accept**	*Reject*
D100A80	24	-2.194	± 2.064	*Reject*	**Accept**
D500A80	24	-2.336	± 2.064	*Reject*	**Accept**
D1000A80	24	-3.112	± 2.064	*Reject*	**Accept**

Table 21 : Akzo Twaron Detergent Ageing Test Results

21a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
T24D23	25	235.3	250.6	217.2	9.3
T100D23	25	236.6	259.9	206.7	11.4
T500D23	25	234.4	261.4	219.2	9.1
T1000D23	25	231.9	248.6	222.2	7.9
T24D80	25	234.8	261.0	211.9	14.1
T100D80	25	225.9	264.5	205.8	13.1
T500D80	25	214.8	227.9	196.4	8.0
T1000D80	25	207.0	231.8	174.2	13.1

21b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
T24D23	24	-0.589	±2.064	**Accept**	*Reject*
T100D23	24	-1.804	±2.064	**Accept**	*Reject*
T500D23	24	-0.824	±2.064	**Accept**	*Reject*
T1000D23	24	-2.035	±2.064	**Accept**	*Reject*
T24D80	24	-0.325	±2.064	**Accept**	*Reject*
T100D80	24	-1.472	±2.064	**Accept**	*Reject*
T500D80	24	-7.636	±2.064	*Reject*	**Accept**
T1000D80	24	-3.793	±2.064	*Reject*	**Accept**

Table 22 : DuPont Kevlar 49 Detergent Ageing Test Results

22a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
K24D23	25	241.6	261.5	217.9	10.0
K100D23	25	227.4	244.7	206.8	9.4
K500D23	25	229.8	258.8	204.4	12.9
K1000D23	25	233.2	262.3	213.2	14.2
K24D80	25	230.8	255.3	205.6	12.1
K100D80	25	226.0	247.7	202.4	13.4
K500D80	25	213.3	244.0	188.9	13.1
K1000D80	25	192.6	227.9	170.1	14.6

22b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
K24D23	24	1.882	±2.064	**Accept**	*Reject*
K100D23	24	-1.055	±2.064	**Accept**	*Reject*
K500D23	24	-0.288	±2.064	**Accept**	*Reject*
K1000D23	24	0.122	±2.064	**Accept**	*Reject*
K24D80	24	-0.183	±2.064	**Accept**	*Reject*
K100D80	24	-0.721	±2.064	**Accept**	*Reject*
K500D80	24	-2.323	±2.064	*Reject*	**Accept**
K1000D80	24	-4.133	±2.064	*Reject*	**Accept**

Table 23 : DSM Dyneema SK65 Detergent Ageing Test Results

23a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
D24D23	25	475.9	499.3	448.1	14.7
D100D23	25	471.3	496.4	448.7	14.4
D500D23	25	470.1	502.0	431.1	15.7
D1000D23	25	451.2	481.8	405.8	17.5
D24D80	25	449.1	486.8	412.8	20.6
D100D80	25	467.9	506.4	429.7	16.8
D500D80	25	468.9	489.2	436.4	12.3
D1000D80	25	459.2	488.6	416.6	16.6

23b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
D24D23	24	-0.250	± 2.064	**Accept**	*Reject*
D100D23	24	-0.747	± 2.064	**Accept**	*Reject*
D500D23	24	-0.771	± 2.064	**Accept**	*Reject*
D1000D23	24	-2.174	± 2.064	*Reject*	**Accept**
D24D80	24	-1.874	± 2.064	**Accept**	*Reject*
D100D80	24	-0.879	± 2.064	**Accept**	*Reject*
D500D80	24	-1.292	± 2.064	**Accept**	*Reject*
D1000D80	24	-1.638	± 2.064	**Accept**	*Reject*

Table 24 : Akzo Twaron Diesel Ageing Test Results

24a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
T24R23	25	239.4	256.8	221.3	8.9
T100R23	25	236.4	251.7	219.8	9.5
T500R23	25	242.2	259.5	219.1	10.4
T1000R23	25	228.1	245.1	210.0	10.0

24b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
T24R23	24	0.398	±2.064	**Accept**	*Reject*
T100R23	24	-0.313	±2.064	**Accept**	*Reject*
T500R23	24	0.824	±2.064	**Accept**	*Reject*
T1000R23	24	-1.940	±2.064	**Accept**	*Reject*

Table 25 : DuPont Kevlar 49 Diesel Ageing Test Results

25a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
K24R23	25	239.0	260.2	212.2	13.7
K100R23	25	238.8	258.2	215.4	12.0
K500R23	25	238.5	256.6	216.1	12.7
K1000R23	25	235.3	257.8	208.3	13.6

25b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
K24R23	24	0.801	± 2.064	**Accept**	*Reject*
K100R23	24	0.997	± 2.064	**Accept**	*Reject*
K500R23	24	0.829	± 2.064	**Accept**	*Reject*
K1000R23	24	0.371	± 2.064	**Accept**	*Reject*

Table 26 : DSM Dyneema SK65 Diesel Ageing Test Results

26a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
K24R23	25	476.3	498.2	452.2	14.6
K100R23	25	479.2	498.2	433.8	16.2
K500R23	25	473.8	497.8	440.0	14.4
K1000R23	25	464.6	497.6	420.2	17.4

26b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
K24R23	24	-0.211	±2.064	**Accept**	*Reject*
K100R23	24	0.079	±2.064	**Accept**	*Reject*
K500R23	24	-0.475	±2.064	**Accept**	*Reject*
K1000R23	24	-1.144	±2.064	**Accept**	*Reject*

Table 27 : Akzo Twaron Petrol Ageing Test Results

27a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
T24P23	25	225.4	250.6	216.8	6.7
T100P23	25	222.8	240.1	202.7	7.9
T500P23	25	223.1	243.3	207.4	6.7
T1000P23	25	219.3	231.7	204.6	7.3

27b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
T24P23	24	-7.195	± 2.064	*Reject*	**Accept**
T100P23	24	-5.193	± 2.064	*Reject*	**Accept**
T500P23	24	-8.639	± 2.064	*Reject*	**Accept**
T1000P23	24	-8.008	± 2.064	*Reject*	**Accept**

Table 28 : DuPont Kevlar 49 Petrol Ageing Test Results

28a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
K24P23	25	221.9	242.1	196.3	11.2
K100P23	25	221.0	241.6	199.3	10.1
K500P23	25	224.5	247.9	212.0	8.0
K1000P23	25	218.1	233.9	198.8	9.5

28b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
K24P23	24	-1.641	$\pm$2.064	**Accept**	*Reject*
K100P23	24	-2.178	$\pm$2.064	*Reject*	**Accept**
K500P23	24	-2.488	$\pm$2.064	*Reject*	**Accept**
K1000P23	24	-3.079	$\pm$2.064	*Reject*	**Accept**

Table 29 : DSM Dyneema SK65 Petrol Ageing Test Results

29a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
D24P23	25	464.6	495.3	435.2	14.7
D100P23	25	451.5	483.1	404.5	19.6
D500P23	25	463.3	492.6	432.4	16.6
D1000P23	25	472.4	494.9	439.9	15.9

29b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
D24P23	24	-1.413	± 2.064	**Accept**	*Reject*
D100P23	24	-1.850	± 2.064	**Accept**	*Reject*
D500P23	24	-1.301	± 2.064	**Accept**	*Reject*
D1000P23	24	-0.539	± 2.064	**Accept**	*Reject*

Table 30 : Akzo Twaron Tap Water Ageing Test Results

30a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
T24W23	25	236.6	267.5	218.5	13.3
T100W23	25	237.8	255.7	214.6	10.5
T500W23	25	223.9	233.7	209.6	6.0
T1000W23	25	222.3	252.2	204.3	11.2
T24W80	25	239.1	258.3	214.0	10.8
T100W80	25	233.0	253.4	219.1	7.5
T500W80	25	221.6	238.5	206.4	8.5
T1000W80	25	217.5	233.8	202.2	7.9

30b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
T24W23	24	-0.148	± 2.064	**Accept**	*Reject*
T100W23	24	0.000	± 2.064	**Accept**	*Reject*
T500W23	24	-14.532	± 2.064	*Reject*	**Accept**
T1000W23	24	-1.576	± 2.064	**Accept**	*Reject*
T24W80	24	0.221	± 2.064	**Accept**	*Reject*
T100W80	24	-1.931	± 2.064	**Accept**	*Reject*
T500W80	24	-2.973	± 2.064	*Reject*	**Accept**
T1000W80	24	-6.918	± 2.064	*Reject*	**Accept**

Table 31 : DuPont Kevlar 49 Tap Water Ageing Test Results

31a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
K24W23	25	236.9	256.6	220.9	9.5
K100W23	25	255.0	252.3	211.8	8.2
K500W23	25	233.7	224.5	213.3	7.8
K1000W23	25	222.3	252.2	204.3	11.2
K24W80	25	231.8	260.0	209.5	12.3
K100W80	25	229.7	244.3	214.9	8.8
K500W80	25	221.6	238.5	204.6	8.5
K1000W80	25	209.3	238.8	193.6	10.6

31b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
K24W23	24	1.067	±2.064	**Accept**	*Reject*
K100W23	24	-2.200	±2.064	*Reject*	**Accept**
K500W23	24	-3.039	±2.064	*Reject*	**Accept**
K1000W23	24	-1.578	±2.064	**Accept**	*Reject*
K24W80	24	-0.043	±2.064	**Accept**	*Reject*
K100W80	24	-0.619	±2.064	**Accept**	*Reject*
K500W80	24	-2.973	±2.064	*Reject*	**Accept**
K1000W80	24	-4.052	±2.064	*Reject*	**Accept**

Table 32 : DSM Dyneema SK65 Tap Water Ageing Test Results

32a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
D24W23	25	439.5	463.7	404.4	15.6
D100W23	25	449.5	471.4	421.8	10.0
D500W23	25	449.4	481.9	416.9	15.0
D1000W23	25	464.1	481.4	438.9	8.8
D24W80	25	446.0	467.6	416.2	14.5
D100W80	25	448.0	463.7	416.5	12.6
D500W80	25	439.5	464.9	404.4	17.0
D1000W80	25	433.5	467.2	435.0	8.8

32b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
D24W23	24	-3.656	± 2.064	*Reject*	**Accept**
D100W23	24	-5.718	± 2.064	*Reject*	**Accept**
D500W23	24	-2.889	± 2.064	*Reject*	**Accept**
D1000W23	24	-3.718	± 2.064	*Reject*	**Accept**
D24W80	24	-3.389	± 2.064	*Reject*	**Accept**
D100W80	24	-3.966	± 2.064	*Reject*	**Accept**
D500W80	24	-3.242	± 2.064	*Reject*	**Accept**
D1000W80	24	-6.453	± 2.064	*Reject*	**Accept**

Table 33 : Akzo Twaron Thermal Ageing Test Results

33a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
T24H100	25	235.2	254.9	221.3	8.9
T100H100	25	227.1	252.9	213.8	8.6
T500H100	25	225.6	258.9	202.3	12.0
T1000H100	25	201.6	236.8	179.5	15.8
T24H150	25	221.7	248.3	200.8	11.7
T100H150	25	187.9	234.8	158.3	20.9
T500H150	25	140.3	199.1	104.0	23.8
T1000H150	25	119.6	155.9	86.0	18.2

33b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
T24H100	24	-0.674	± 2.064	**Accept**	*Reject*
T100H100	24	-2.939	± 2.064	*Reject*	**Accept**
T500H100	24	-1.745	± 2.064	**Accept**	*Reject*
T1000H100	24	-3.347	± 2.064	*Reject*	**Accept**
T24H150	24	-2.421	± 2.064	*Reject*	**Accept**
T100H150	24	-3.139	± 2.064	*Reject*	**Accept**
T500H150	24	-5.189	± 2.064	*Reject*	**Accept**
T1000H150	24	-8.493	± 2.064	*Reject*	**Accept**

Table 34 : DuPont Kevlar 49 Thermal Ageing Test Results

34a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
K24H100	25	231.4	253.3	214.8	12.0
K100H100	25	207.9	230.2	193.4	10.6
K500H100	25	175.2	216.0	143.7	20.7
K1000H100	25	173.4	213.6	136.8	20.2
K24H150	25	200.6	219.5	181.1	10.3
K100H150	25	182.7	210.8	161.3	14.6
K500H150	25	119.6	155.9	86.0	18.2
K1000H150	25	95.3	122.8	58.0	16.2

34b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
K24H100	24	-0.093	$\pm$2.064	**Accept**	*Reject*
K100H100	24	-4.335	$\pm$2.064	*Reject*	**Accept**
K500H100	24	-3.622	$\pm$2.064	*Reject*	**Accept**
K1000H100	24	-3.862	$\pm$2.064	*Reject*	**Accept**
K24H150	24	-5.925	$\pm$2.064	*Reject*	**Accept**
K100H150	24	-5.137	$\pm$2.064	*Reject*	**Accept**
K500H150	24	-8.693	$\pm$2.064	*Reject*	**Accept**
K1000H150	24	-12.194	$\pm$2.064	*Reject*	**Accept**

Table 35 : DSM Dyneema SK65 Thermal Ageing Test Results

35a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
D24H100	25	364.0	404.7	326.9	23.4
D100H100	25	213.0	367.7	245.6	38.0
D500H100	25	285.0	373.8	230.1	24.4
D1000H100	25	343.9	403.5	295.6	29.0
D24H125	25	171.2	249.4	119.3	36.4
D100H125	25	29.6	39.0	34.0	15.0
D500H125	25	N/A	N/A	N/A	N/A
D1000H125	25	N/A	N/A	N/A	N/A

35b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
D24H100	24	-6.196	±2.064	*Reject*	**Accept**
D100H100	24	-5.010	±2.064	*Reject*	**Accept**
D500H100	24	-9.969	±2.064	*Reject*	**Accept**
D1000H125	24	-5.602	±2.064	*Reject*	**Accept**
D24H125	24	-9.766	±2.064	*Reject*	**Accept**
D100H125	24	-44.686	±2.064	*Reject*	**Accept**
D500H125	24	N/A	±2.064	N/A	N/A
D1000H125	24	N/A	±2.064	N/A	N/A

Table 36 : Akzo Twaron Ultra Violet Ageing Test Results

36a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
T24U50	25	215.4	233.0	179.0	12.5
T100U50	25	211.1	226.4	199.8	8.1
T500U50	25	167.1	202.1	119.2	15.4
T1000U50	25	130.6	155.6	107.5	15.5

36b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
T24U50	24	-2.988	± 2.064	*Reject*	**Accept**
T100U50	24	-8.556	± 2.064	*Reject*	**Accept**
T500U50	24	-6.820	± 2.064	*Reject*	**Accept**
T1000U50	24	-10.256	± 2.064	*Reject*	**Accept**

Table 37 : Dupont Kevlar 49 Ultra Violet Ageing Test Results

37a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
K24U50	25	220.0	255.2	188.8	11.7
K100U50	25	209,9	241.7	177.8	14.6
K500U50	25	173.4	206.7	145.9	17.5
K1000U50	25	149.0	191.0	116.7	20.2

37b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
K24U50	24	-1.822	±2.064	**Accept**	*Reject*
K100U50	24	-2.316	±2.064	*Reject*	**Accept**
K500U50	24	-4.705	±2.064	*Reject*	**Accept**
K1000U50	24	-5.464	±2.064	*Reject*	**Accept**

Table 38 : DSM Dyneema SK65 Ultra Violet Ageing Test Results

38a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
D24U50	25	436.0	486.0	382.7	29.3
D100U50	25	249.6	299.4	152.6	39.6
D500U50	25	N/A	N/A	N/A	N/A
D1000U50	25	N/A	N/A	N/A	N/A

38b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
D24U50	24	-1.743	±2.064	**Accept**	*Reject*
D100U50	24	-6.615	±2.064	*Reject*	**Accept**
D500U50	24	N/A	±2.064	N/A	N/A
D1000U50	24	N/A	±2.064	N/A	N/A

Table 39 : Akzo Twaron Saturated Salt Water Ageing Test Results

39a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
T24S23	25	227.7	257.1	212.8	11.1
T100S23	25	241.1	259.0	220.9	11.3
T500S23	25	233.0	254.2	208.5	11.6
T1000S23	25	231.7	260.3	211.6	10.0
T24S80	25	233.2	261.5	215.0	11.0
T100S80	25	223.7	238.3	213.0	7.2
T500S80	25	220.3	251.2	208.4	9.6
T1000S80	25	214.0	233.8	187.2	10.7

39b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
T24S23	24	-1.639	± 2.064	**Accept**	*Reject*
T100S23	24	0.528	± 2.064	**Accept**	*Reject*
T500S23	24	-0.728	± 2.064	**Accept**	*Reject*
T1000S23	24	-1.229	± 2.064	**Accept**	*Reject*
T24S80	24	-0.767	± 2.064	**Accept**	*Reject*
T100S80	24	-6.376	± 2.064	*Reject*	**Accept**
T500S80	24	-3.795	± 2.064	*Reject*	**Accept**
T1000S80	24	-4.149	± 2.064	*Reject*	**Accept**

Table 40 : DuPont Kevlar 49 Saturated Salt Water Ageing Test Results

40a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
K24S23	25	236.3	236.3	216.7	11.8
K100S23	25	221.0	238.5	198.6	11.0
K500S23	25	231.2	251.1	214.4	9.2
K1000S23	25	236.0	252.0	212.2	10.2
K24S80	25	234.7	263.4	213.7	10.8
K100S80	25	216.3	235.5	189.9	10.6
K500S80	25	217.3	265.0	192.5	17.1
K1000S80	25	207.8	236.7	163.3	16.3

40b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
K24S23	24	0.618	±2.064	**Accept**	*Reject*
K100S23	24	-1.848	±2.064	**Accept**	*Reject*
K500S23	24	-0.214	±2.064	**Accept**	*Reject*
K1000S23	24	0.756	±2.064	**Accept**	*Reject*
K24S80	24	0.456	±2.064	**Accept**	*Reject*
K100S80	24	-2.811	±2.064	*Reject*	**Accept**
K500S80	24	-1.225	±2.064	**Accept**	*Reject*
K1000S80	24	-2.149	±2.064	*Reject*	**Accept**

Table 41 : DSM Dyneema SK65 Saturated Salt Water Ageing Test Results

41a : Results

Ageing Test	Sample Size	Ave Break Load (N)	Max Ave Break Load (N)	Min Ave Break Load (N)	Ave Break Load SD (N)
D24S23	25	459.6	492.1	389.9	21.6
D100S23	25	444.5	469.4	415.0	12.9
D500S23	25	469.1	494.1	427.8	17.8
D1000S23	25	466.5	490.6	430.5	14.8
D24S80	25	434.5	467.0	393.3	15.9
D100S80	25	446.1	467.5	422.8	13.8
D500S80	25	451.6	477.6	427.1	12.8
D1000S80	25	428.8	453.8	406.8	12.1

41b : Students t-Test

Ageing Test	DOF	t-Test Value	Critical Value	**H0** Ave as Unaged	**H1** Ave not as Unaged
D24S23	24	-1.127	±2.064	**Accept**	*Reject*
D100S23	24	-4.247	±2.064	*Reject*	**Accept**
D500S23	24	-0.720	±2.064	**Accept**	*Reject*
D1000S23	24	-1.211	±2.064	**Accept**	*Reject*
D24S80	24	-4.016	±2.064	*Reject*	**Accept**
D100S80	24	-3.669	±2.064	*Reject*	**Accept**
D500S80	24	-3.426	±2.064	*Reject*	**Accept**
D1000S80	24	-6.997	±2.064	*Reject*	**Accept**

Table 42 : Unaged Yarn LASE Test Results Table

42a : Unaged LASE Test Results for Akzo Twaron (1610 dtex)

Sample Unaged	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	63	121	69.2	112.5	N/A
S.D.	2.8	3.6	0.5	1.0	N/A

42b : Unaged LASE Test Results for DuPont Kevlar 49 (1580 dtex)

Sample Unaged	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	62	119	70.5	110.7	N/A
S.D.	2.9	3.6	0.2	5.7	N/A

42c : Unaged LASE Test Results for DSM Dyneema SK65 (1760 dtex)

Sample Unaged	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	66	122	62.4	72.1	N/A
S.D.	4.2	5.0	69.7	5.9	N/A

Table 43 : Acid Ageing LASE Test Results Table

43a : Acid Aged LASE Test Results for Akzo Twaron (1610 dtex)

Sample T1000C23	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	64	N/A	70.9	114.8	100.6
S.D.	1.5	N/A	2.6	2.7	3.7

43b : Acid Aged LASE Test Results for DuPont Kevlar 49 (1580 dtex)

Sample K1000C23	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	59	116	63.3	94.0	91.5
S.D.	5.1	6.2	4.1	2.6	5.9

43c : Acid Aged LASE Test Results for DSM Dyneema SK65 (1760 dtex)

Sample D1000C23	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	54	113	58.7	59.4	94.0
S.D.	5.1	4.1	1.6	5.6	2.6

Table 44 : Alkali Ageing LASE Test Results Table

44a : Alkali Aged LASE Test Results for Akzo Twaron (1610 dtex)

Sample T1000A23	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	58	113	62.4	104.7	90.1
S.D.	3.2	5.5	3.2	5.7	4.7

44b : Alkali Aged LASE Test Results for DuPont Kevlar 49 (1580 dtex)

Sample K1000A23	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	58	115	64.7	104.1	91.8
S.D.	1.5	2.3	1.7	2.7	2.5

44c : Alkali Aged LASE Test Results for DSM Dyneema SK65 (1760 dtex)

Sample D1000A23	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	62	117	60.1	67.8	96.2
S.D.	3.0	5.6	1.4	3.2	2.3

Table 45 : Detergent Ageing LASE Test Results Table

45a : Detergent Aged LASE Test Results for Akzo Twaron (1610 dtex)

Sample T1000D80	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	64	123	69.4	115.5	100.3
S.D.	2.5	2.3	0.7	4.5	1.0

45b : Detergent Aged LASE Test Results for DuPont Kevlar 49 (1580 dtex)

Sample K1000D80	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	57	116	68.4	103.0	97.7
S.D.	4.0	4.8	2.4	7.2	3.4

45c : Detergent Aged LASE Test Results for DSM Dyneema SK65 (1760 dtex)

Sample D1000D80	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	54	103	55.1	59.7	88.2
S.D.	7.5	10.6	5.7	8.2	9.1

Table 46 : Diesel Ageing LASE Test Results Table

46a : Diesel Aged LASE Test Results for Akzo Twaron (1610 dtex)

Sample T1000R23	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	63	122	70.3	112.5	101.5
S.D.	1.0	1.2	0.9	1.8	1.3

46b : Diesel Aged LASE Test Results for DuPont Kevlar 49 (1580 dtex)

Sample K1000R23	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	60	113	69.6	107.7	96.7
S.D.	4.2	5.5	3.4	7.4	4.8

46c : Diesel Aged LASE Test Results for DSM Dyneema SK65 (1760 dtex)

Sample D1000R23	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	64	121	64.1	70.3	98.7
S.D.	3.5	6.8	3.7	3.8	5.3

Table 47 : Petrol Ageing LASE Test Results Table

47a : Petrol Aged LASE Test Results for Akzo Twaron (1610 dtex)

Sample T1000P23	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	60	119	69.0	108.3	99.6
S.D.	1.5	1.3	0.4	2.7	0.5

47b : Petrol Aged LASE Test Results for DuPont Kevlar 49 (1580 dtex)

Sample K1000P23	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	63	118	72.3	112.5	102.6
S.D.	1.0	10.3	1.1	1.8	1.6

47c : Petrol Aged LASE Test Results for DSM Dyneema SK65 (1760 dtex)

Sample D1000P23	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	56	113	59.8	61.9	86.4
S.D.	4.7	6.1	4.3	5.2	6.2

Table 48 : Tap Water Ageing LASE Test Results Table

48a : Tap Water Aged LASE Test Results for Akzo Twaron (1610 dtex)

Sample T1000W80	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	63	121	68.5	112.5	99.0
S.D.	1.0	1.6	0.7	1.8	1.0

48b : Tap Water Aged LASE Test Results for DuPont Kevlar 49 (1580 dtex)

Sample K1000W80	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	62	121	67.9	111.3	96.4
S.D.	3.1	3.2	1.6	5.5	2.3

48c : Tap Water Aged LASE Test Results for DSM Dyneema SK65 (1760 dtex)

Sample D1000W80	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	68	126	67.1	74.3	107.4
S.D.	4.6	7.5	4.5	5.0	7.3

Table 49 : Thermal Ageing LASE Test Results Table

49a : Thermal Ageing LASE Test Results for Akzo Twaron (1610 dtex)

Sample T1000T150	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	63	123	67.7	113.7	97.8
S.D.	2.5	4.6	2.7	4.5	3.9

49b : Thermal Ageing LASE Test Results for DuPont Kevlar 49 (1580 dtex)

Sample K1000T150	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	62	N/A	66	111.3	94.4
S.D.	3.1	N/A	2.9	5.5	4.1

49c : Thermal Ageing LASE Test Results for DSM Dyneema SK65 (1760 dtex)

Sample D1000T100	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	50	93	48.3	55.0	77.3
S.D.	1.5	4.2	2.3	1.7	3.8

Table 50 : Ultra Violet Ageing LASE Test Results Table

50a : Ultra Violet Aged LASE Test Results for Akzo Twaron (1610 dtex)

Sample T1000U50	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	62	119	67.8	111.9	101.3
S.D.	3.2	2.9	2.1	5.7	3.0

50b : Ultra Violet Aged LASE Test Results for DuPont Kevlar 49 (1580 dtex)

Sample K1000U50	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	62	119	67.3	110.7	95.5
S.D.	2.6	5.7	3.2	4.7	4.6

50c : Ultra Aged LASE Test Results for DSM Dyneema SK65 (1760 dtex)

Sample D1000U50	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	N/A	N/A	N/A	N/A	N/A
S.D.	N/A	N/A	N/A	N/A	N/A

Table 51 : Saturated Salt Water Ageing LASE Test Results Table

51a : Saturated Salt Water Aged LASE Test Results for Akzo Twaron (1610 dtex)

Sample T1000S80	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	61	121	68.6	110.1	99.2
S.D.	0.6	1.2	0.5	1.0	0.7

51b : Saturated Salt Water Aged LASE Test Results for DuPont Kevlar 49 (1580 dtex)

Sample K1000S80	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	57	120	71.1	102.4	100.9
S.D.	3.2	6.1	2.3	5.7	3.2

51c : Saturated Salt Water Aged LASE Test Results for DSM Dyneema SK65 (1760 dtex)

Sample D1000S80	Load @ 0.5% Strain (N)	Load @ 1.0% Strain (N)	Youngs Modulus (N/tex)	Youngs Modulus (GPa)	Youngs Modulus (% of unaged)
Average	50	101	54.0	54.6	86.5
S.D.	12.3	16.9	4.1	13.4	6.6

Table 52 : Unaged Yarn Fatigue Test Results Table

52a : Unaged Fatigue Test Results for Akzo Twaron (1610 dtex)

Sample Unaged	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	#B
Average	10,000	63	0.5	225.6	94.9	100
S.D.	N/A	N/A	N/A	6.7	2.8	2.9

52b : Unaged Fatigue Test Results for DuPont Kevlar 49 (1580 dtex)

Sample Unaged	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	#B
Average	10,000	62	0.5	222.1	93.4	100
S.D.	N/A	N/A	N/A	14.0	6.0	6.3

52c : Unaged Fatigue Test Results for DSM Dyneema SK65 (1760 dtex)

Sample Unaged	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	#B
Average	10,000	66	0.5	401.0	83.8	100
S.D.	N/A	N/A	N/A	10.1	2.1	2.5

* Column **A** refers to the tensile strength of aged fatigue tested yarn as a percentage of the tensile strength of unaged non fatigue tested yarn.

Column **B** refers to the tensile strength of aged fatigue tested yarn as a percentage of the tensile strength of unaged fatigue tested yarn.

Table 53 : Acid Aged Fatigue Test Results Table

53a : Acid Aged Fatigue Test Results for Akzo Twaron (1610 dtex)

Sample T1000C23	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	#B
Average	10,000	63	0.5	112.6	47.3	49.9
S.D.	N/A	N/A	N/A	23.1	9.7	10.2

53b : Acid Aged Fatigue Test Results for DuPont Kevlar 49 (1580 dtex)

Sample K1000C23	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	#B
Average	10,000	62	0.5	83.8	36.1	37.7
S.D.	N/A	N/A	N/A	41.4	17.8	18.7

53c : Acid Aged Fatigue Test Results for DSM Dyneema SK65 (1760 dtex)

Sample D1000C23	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	#B
Average	10,000	66	0.5	326.2	68.1	81.3
S.D.	N/A	N/A	N/A	71.4	14.9	17.6

* Column **A** refers to the tensile strength of aged fatigue tested yarn as a percentage of the tensile strength of unaged non fatigue tested yarn.

Column **B** refers to the tensile strength of aged fatigue tested yarn as a percentage of the tensile strength of unaged fatigue tested yarn.

Table 54 : Alkali Aged Fatigue Test Results Table

54a : Alkali Aged Fatigue Test Results for Akzo Twaron (1610 dtex)

Sample T1000A23	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	′B
Average	10,000	63	0.5	122.2	51.4	54.2
S.D.	N/A	N/A	N/A	16.6	7.0	7.4

54b : Alkali Aged Fatigue Test Results for DuPont Kevlar 49 (1580 dtex)

Sample K1000A23	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	′B
Average	10,000	62	0.5	132.9	57.2	59.8
S.D.	N/A	N/A	N/A	13.8	6.0	6.2

54c : Alkali Aged Fatigue Test Results for DSM Dyneema SK65 (1760 dtex)

Sample D1000A23	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	′B
Average	10,000	66	0.5	416.3	86.4	103.8
S.D.	N/A	N/A	N/A	9.0	2.8	2.2

* Column A refers to the tensile strength of aged fatigue tested yarn as a percentage of the tensile strength of unaged non fatigue tested yarn.

′ Column B refers to the tensile strength of aged fatigue tested yarn as a percentage of the tensile strength of unaged fatigue tested yarn.

Table 55 : Detergent Aged Fatigue Test Results Table

55a : Detergent Aged Fatigue Test Results for Akzo Twaron (1610 dtex)

Sample T1000D80	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	♯B
Average	10,000	63	0.5	187.0	78.6	82.9
S.D.	N/A	N/A	N/A	13.2	5.5	5.8

55b : Detergent Aged Fatigue Test Results for DuPont Kevlar 49 (1580 dtex)

Sample K1000D80	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	♯B
Average	10,000	62	0.5	184.7	79.5	83.1
S.D.	N/A	N/A	N/A	14.9	6.4	6.7

55c : Detergent Aged Fatigue Test Results for DSM Dyneema SK65 (1760 dtex)

Sample D1000D80	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	♯B
Average	10,000	66	0.5	381.1	79.6	90.0
S.D.	N/A	N/A	N/A	56.3	11.8	9.8

* Column **A** refers to the tensile strength of aged fatigue tested yarn as a percentage of the tensile strength of unaged non fatigue tested yarn.

♯ Column **B** refers to the tensile strength of aged fatigue tested yarn as a percentage of the tensile strength of unaged fatigue tested yarn.

Table 56 : Diesel Aged Fatigue Test Results Table

56a : Diesel Aged Fatigue Test Results for Akzo Twaron (1610 dtex)

Sample T1000R23	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	#B
Average	10,000	63	0.5	200.4	84.3	88.8
S.D.	N/A	N/A	N/A	27.2	11.5	12.1

56b : Diesel Aged Fatigue Test Results for DuPont Kevlar 49 (1580 dtex)

Sample K1000R23	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	#B
Average	10,000	62	0.5	183.3	78.9	82.5
S.D.	N/A	N/A	N/A	22.4	9.7	10.1

56c : Diesel Aged Fatigue Test Results for DSM Dyneema SK65 (1760 dtex)

Sample D1000R23	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	#B
Average	10,000	66	0.5	399.5	83.5	96.8
S.D.	N/A	N/A	N/A	49.8	10.4	12.3

* Column **A** refers to the tensile strength of aged fatigue tested yarn as a percentage of the tensile strength of unaged non fatigue tested yarn.

Column **B** refers to the tensile strength of aged fatigue tested yarn as a percentage of the tensile strength of unaged fatigue tested yarn.

Table 57 : Petrol Aged Fatigue Test Results Table

57a : Petrol Aged Fatigue Test Results for Akzo Twaron (1610 dtex)

Sample T1000P23	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	#B
Average	10,000	63	0.5	186.5	78.4	82.7
S.D.	N/A	N/A	N/A	18.2	7.7	8.1

57b : Petrol Aged Fatigue Test Results for DuPont Kevlar 49 (1580 dtex)

Sample K1000P23	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	#B
Average	10,000	62	0.5	200.4	86.3	90.2
S.D.	N/A	N/A	N/A	24.1	10.4	10.2

57c : Petrol Aged Fatigue Test Results for DSM Dyneema SK65 (1760 dtex)

Sample D1000R23	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	#B
Average	10,000	66	0.5	380.8	79.6	91.7
S.D.	N/A	N/A	N/A	43.4	9.1	9.2

* Column **A** refers to the tensile strength of aged fatigue tested yarn as a percentage of the tensile strength of unaged non fatigue tested yarn.

Column **B** refers to the tensile strength of aged fatigue tested yarn as a percentage of the tensile strength of unaged fatigue tested yarn.

Table 58 : Tap Water Aged Fatigue Test Results Table

58a : Tap Water Aged Fatigue Test Results for Akzo Twaron (1610 dtex)

Sample T1000W80	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strenth as % of virgin yarn (%)	
					*A	′B
Average	10,000	63	0.5	181.6	76.4	80.5
S.D.	N/A	N/A	N/A	24.3	10.2	10.6

58b : Tap Water Aged Fatigue Test Results for DuPont Kevlar 49 (1580 dtex)

Sample K1000W80	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	′B
Average	10,000	62	0.5	195.5	84.2	88.0
S.D.	N/A	N/A	N/A	8.2	3.5	3.7

58c : Tap Water Aged Fatigue Test Results for DSM Dyneema SK65 (1760 dtex)

Sample D1000W80	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength a % of virgin yarn (%)	
					*A	′B
Average	10,000	66	0.5	363.4	75.9	90.8
S.D.	N/A	N/A	N/A	51.5	10.8	14.8

* Column **A** refers to the tensile strength of aged fatigue tested yarn as a percentage of the tensile strength of unaged non fatigue tested yarn.

′ Column **B** refers to the tensile strength of aged fatigue tested yarn as a percentage of the tensile strength of unaged fatigue tested yarn.

Table 59 : Thermal Ageing Fatigue Test Results Table

59a : Thermal Ageing Fatigue Test Results for Akzo Twaron (1610 dtex)

Sample T1000T150	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	#B
Average	10,000	63	0.5	119.7	50.4	53.1
S.D.	N/A	N/A	N/A	17.0	7.1	7.5

59b : Thermal Ageing Fatigue Test Results for DuPont Kevlar 49 (1580 dtex)

Sample K1000T150	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	#B
Average	10,000	62	0.5	71.4	30.7	32.1
S.D.	N/A	N/A	N/A	15.5	6.7	7.0

59c : Thermal Ageing Fatigue Test Results for DSM Dyneema SK65 (1760 dtex)

Sample D1000T100	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	#B
Average	10,000	66	0.5	290.6	60.7	70.7
S.D.	N/A	N/A	N/A	35.6	7.4	9.2

* Column **A** refers to the tensile strength of aged fatigue tested yarn as a percentage of the tensile strength of unaged non fatigue tested yarn.

Column **B** refers to the tensile strength of aged fatigue tested yarn as a percentage of the tensile strength of unaged fatigue tested yarn.

Table 60 : Ultra Violet Aged Fatigue Test Results Table

60a : Ultra Violet Aged Fatigue Test Results for Akzo Twaron (1610 dtex)

Sample T1000U50	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	#B
Average	10,000	63	0.5	135.9	57.2	60.2
S.D.	N/A	N/A	N/A	31.2	13.1	13.8

60b : Ultra Violet Aged Fatigue Test Results for DuPont Kevlar 49 (1580 dtex)

Sample K1000U50	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	#B
Average	10,000	62	0.5	139.3	60.0	62.7
S.D.	N/A	N/A	N/A	24.4	10.5	11.0

60c : Ultra Violet Aged Fatigue Test Results for DSM Dyneema SK65 (1760 dtex)

Sample D1000U50	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	#B
Average	10,000	66	0.5	0.0	0.0	0.0
S.D.	N/A	N/A	N/A	0.0	0.0	0.0

* Column **A** refers to the tensile strength of aged fatigue tested yarn as a percentage of the tensile strength of unaged non fatigue tested yarn.

\# Column **B** refers to the tensile strength of aged fatigue tested yarn as a percentage of the tensile strength of unaged fatigue tested yarn.

Table 61 : Saturated Salt Water Aged Fatigue Test Results Table

61a : SSW Aged Fatigue Test Results for Akzo Twaron (1610 dtex)

Sample T1000S80	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	#B
Average	10,000	63	0.5	175.2	73.7	77.7
S.D.	N/A	N/A	N/A	16.2	6.8	7.2

61b : SSW Aged Fatigue Test Results for DuPont Kevlar 49 (1580 dtex)

Sample K1000S80	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	#B
Average	10,000	62	0.5	182.3	78.5	82.1
S.D.	N/A	N/A	N/A	24.2	10.4	10.8

61c : SSW Aged Fatigue Test Results for DSM Dyneema SK65 (1760 dtex)

Sample D1000S80	Number of Fatigue Cycles	Maximum Load (N)	Maximum Strain (%)	Tensile Breaking Load (N)	Strength as % of virgin yarn (%)	
					*A	#B
Average	10,000	66	0.5	357.1	74.6	87.4
S.D.	N/A	N/A	N/A	18.4	3.8	3.0

* Column **A** refers to the tensile strength of aged fatigue tested yarn as a percentage of the tensile strength of unaged non fatigue tested yarn.

\# Column **B** refers to the tensile strength of aged fatigue tested yarn as a percentage of the tensile strength of unaged fatigue tested yarn.

Table 62 : Outdoor Weathering Results

Test : Oudoor weathering of DuPont Kevlar 49 (1580 dtex) at 0.5% strain in accordance with BS 2782 : Part 5 : 550A.
No of Samples : 10
Start Date : 6\8\92

No	Failure Detection Date	Test Duration (days to failure)
1	16\8\92	10(excluded)
2	24\5\93	292
3	25\6\93	322
4	2\7\93	330
5	9\7\93	337
6	9\7\93	337
7	16\7\93	344
8	16\7\93	344
9	23\7\93	351
10	13\8\93	375
	Mean	337